Analysis of supernova neutrino fluxes

and neutron star properties

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5th April 2019

List of publications

A. Gallo Rosso *et al*. JCAP 1812 (2018) no.12, 006.
V. Gentile *et al*. JCAP 2018 (2018) no.08, 015.
A. Gallo Rosso *et al*. JCAP 1804 (2018) no.04, 040.
A. Gallo Rosso *et al*. JCAP 1711 (2017) no.11, 036.

Theoretical Papers

A. Gallo Rosso *et al*. EPJ Plus 133 (2018) no.7, 267.
G. Fantini *et al*. [ISBN:9789813226081].

Theoretical Reviews

E. Aprile *et al.* Phys.Rev.Lett. 122 (2019) 071301.
E. Aprile *et al.* Phys.Rev.Lett. 121 (2018) no.11, 111302.
E. Aprile *et al.* Phys.Rev. D97 (2018) no.9, 092007.
E. Aprile *et al.* Phys.Rev. D96 (2017) no.12, 122002.
E. Aprile *et al.* Eur.Phys.J. C77 (2017) no.12, 881.
E. Aprile *et al.* Eur.Phys.J. C78 (2018) no.2, 132.
E. Aprile *et al.* Phys.Rev.Lett. 119 (2017) no.18, 181301.
E. Aprile *et al.* Phys.Rev. D96 (2017) no.4, 042004.
E. Aprile *et al.* Eur.Phys.J. C77 (2017) no.12, 890.
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XENON collaboration

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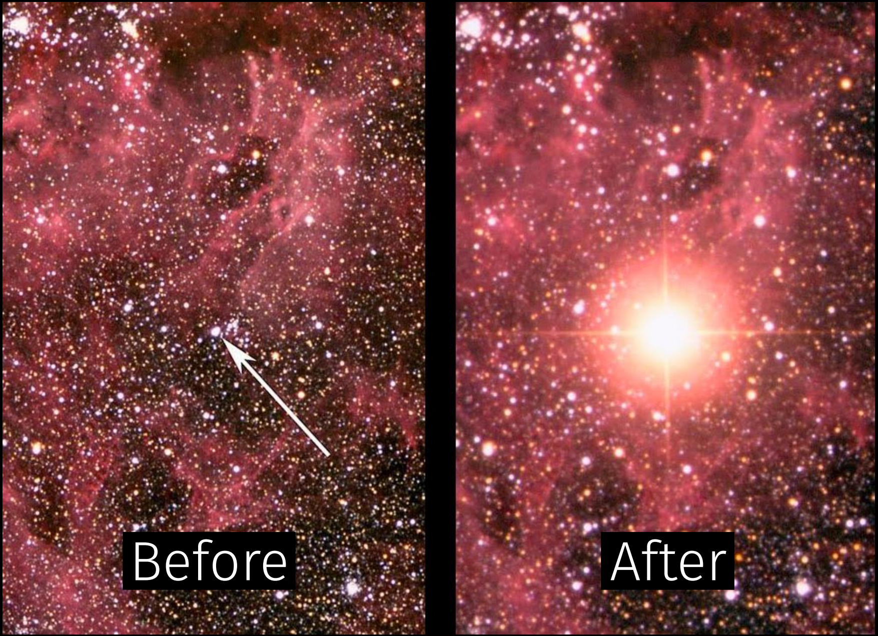
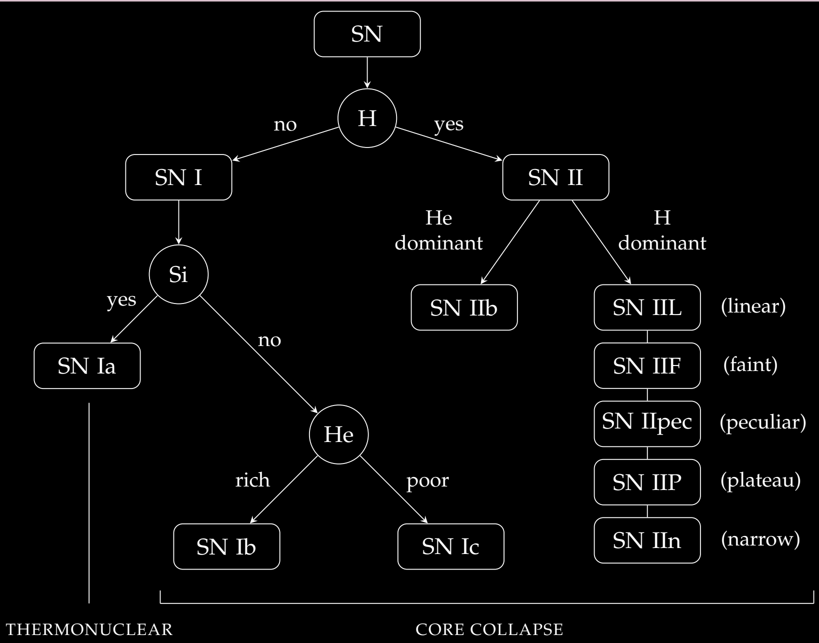
Introduction



SN 1987A

Introduction


SN

H

no

yes

SN I

SN II

Si

He dominant

H dominant

yes

no

SN Ia

SN IIb

SN IIL (linear)

SN IIF (faint)

SN IIpec (peculiar)

SN IIP (plateau)

SN IIn (narrow)

He

rich

poor

SN Ib

SN Ic

THERMONUCLEAR

CORE COLLAPSE

Introduction

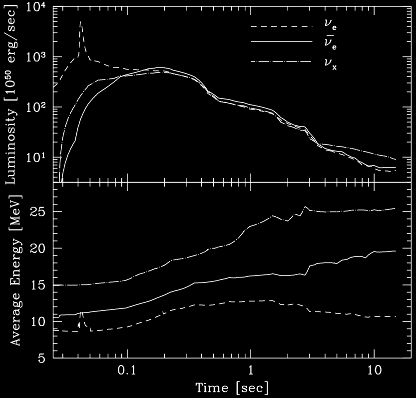
CORE-COLLAPSE SUPERNOVA EXPLOSION

- Longstanding open question in astrophysics
- $\sim 10^{53}$ erg gravitational binding energy
  - 99% emitted in neutrinos
- $\sim 10\,\mathrm{s}$ signal
- Delayed-accretion paradigm
  - From Wilson (1971) & Bethe and Wilson (1985)
  - To 2D & 3D numerical simulations

Introduction

DELAYED EXPLOSION

1. Instability & collapse
2. Bounce & shock propagation
3. Stallation & accretion
4. Cooling



T. Totani et al., Astrophys. J. 496 (1998).

Introduction

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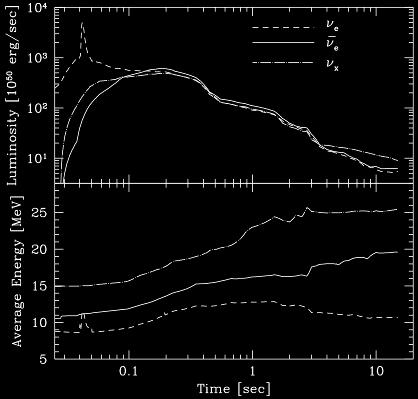

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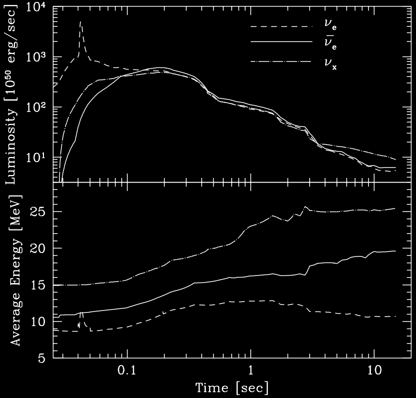

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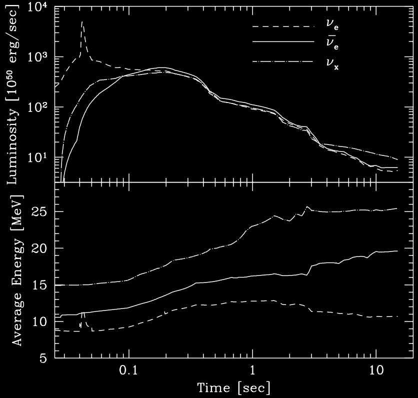

T. Totani et al., Astrophys. J. 496 (1998).

Introduction

NEUTRINO MESSENGERS

- Weakly interacting
    - 99% of binding energy emitted in neutrinos
- 6 flavors: ν_e ν_μ ν_τ $\overline{\nu}_\mathrm{e}$ $\overline{\nu}_\mu$ $\overline{\nu}_\tau$
- Flavor transformation
    - Vacuum: determined with good accuracy
    - Matter conversion: Mikheyev-Smirnov-Wolfenstein effect (MSW) [1]
    - Self-interaction effects in dense media still studied

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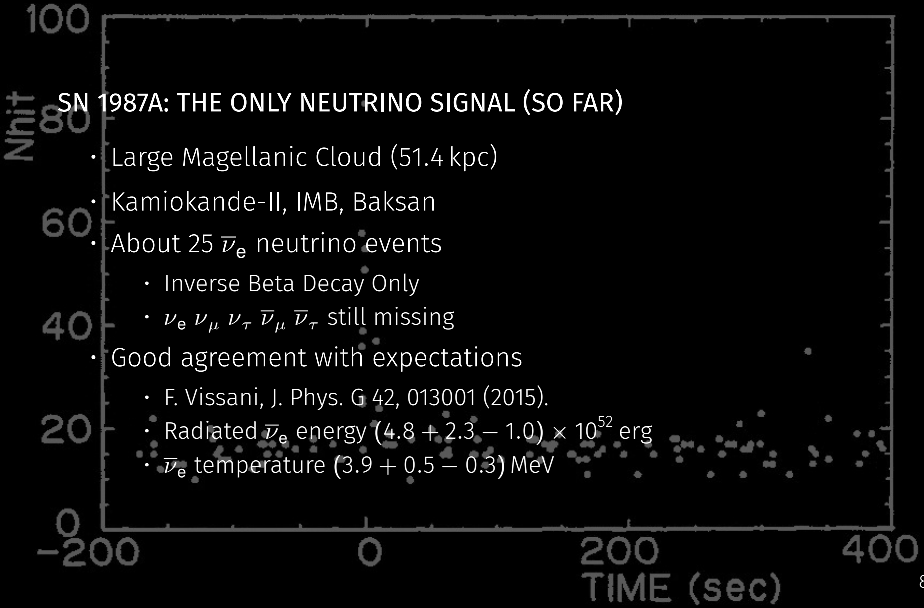
[1] L. Wolfenstein, Phys. Rev. D17 (1978).
S.P. Mikheyev and A.Y. Smirnov, Sov. J. Nucl. Phys. 42 (1985).

Introduction

WHAT CAN WE LEARN FROM SUPERNOVA NEUTRINOS?

- Star properties
    - Pointing and alert (SNEWS)
    - Standard candle (ν_{e} burst)
    - Explosion mechanism
- Particle properties
    - Flavor conversion in dense media
    - Non-standard properties

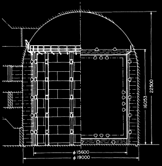
Introduction



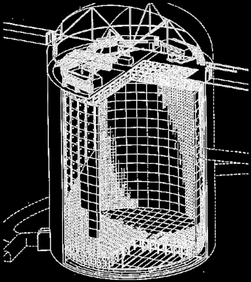
SN 1987A: THE ONLY NEUTRINO SIGNAL (SO FAR)

- Large Magellanic Cloud (51.4 kpc)
- Kamiokande-II, IMB, Baksan
- About 25 $\overline{\nu}_e$ neutrino events
  - Inverse Beta Decay Only
  - ν_e ν_μ ν_τ $\overline{\nu}_\mu$ $\overline{\nu}_\tau$ still missing
- Good agreement with expectations
  - F. Vissani, J. Phys. G 42, 013001 (2015).
  - Radiated $\overline{\nu}_e$ energy $(4.8 + 2.3 - 1.0) \times 10^{52}$ erg
  - $\overline{\nu}_e$ temperature $(3.9 + 0.5 - 0.3)$ MeV

Introduction

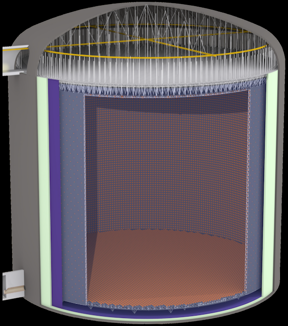


Kamiokande-II



$\sim 10\times$

Super-Kamiokande

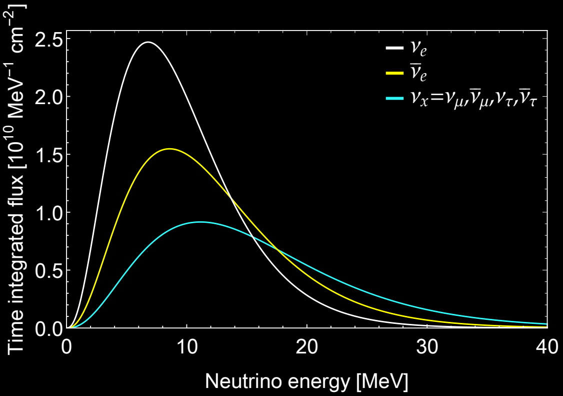


$\sim 10\times$

Hyper-Kamiokande

MANY DETECTION CHANNELS — ENERGY, TIME, FLAVOR

Introduction



TIME INTEGRATED FLUX (FLUENCE)

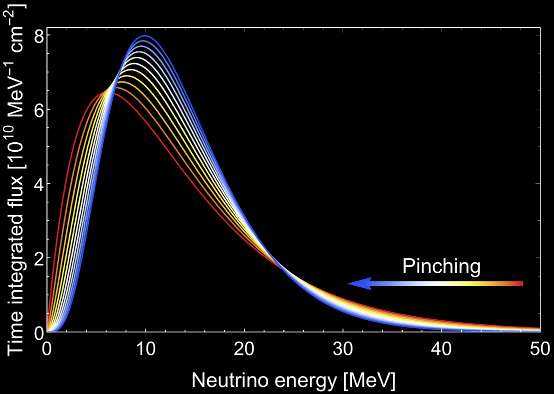
Total energy $\mathcal{E}$ ⇔ normalization

Mean energy $\langle E \rangle$ ⇔ 1^{st} moment

Pinching α ⇔ width

3 PARAMETERS × 3 SPECIES = 9 D.O.F.

Introduction



TIME INTEGRATED FLUX (FLUENCE)

$$\begin{aligned} \text{Total energy } \mathcal{E} &\quad\Leftrightarrow\quad \text{normalization} \\ \text{Mean energy } \langle E \rangle &\quad\Leftrightarrow\quad 1^{\text{st}} \text{ moment} \\ \text{Pinching } \alpha &\quad\Leftrightarrow\quad \text{width} \end{aligned}$$

3 PARAMETERS × 3 SPECIES = 9 D.O.F.

Introduction

NUMBER OF PARAMETERS ARBITRARILY REDUCED

- Lu *et al.* [2] JUNO detector
- Importance of combining channels
  - $\mathcal{E}_{\overline{\nu}_e}$ up to 5% @ 90% C.L.
  - $\langle E_{\overline{\nu}_e} \rangle$ up to 1% @ 90% C.L.

$\Big\downarrow$ with MSW transformation
w/o equipartition ($\mathcal{E}_{\text{tot}} \neq \mathcal{E}_i/6$)

$\mathcal{E}_{\text{tot}}$ known up to 13%

but for spectral shape (i.e. pinching) fully known

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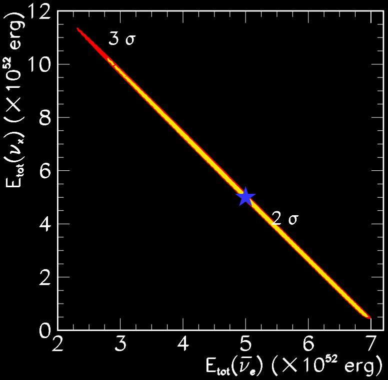
[2] Lu *et al.* Phys. Rev. D 94, 023006 (2016).

Introduction

DIFFICULTY IN RECONSTRUCTING THE BINDING ENERGY

- H. Minakata *et al.* [3]
- Hyper-Kamiokande
- only $\overline{\nu}_e + p \rightarrow e^+ + n$
- If pinching unknown
  - $\mathcal{E}_{\overline{\nu}_e}$ acc. 50% @ 3σ
  - $\langle E_{\overline{\nu}_e} \rangle$ acc. 4% @ 3σ
  - Parameter degeneracy



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

WHAT CAN WE LEARN FROM SUPERNOVA NEUTRINOS?

- How well can we reconstruct the neutrino fluxes without any usual assumptions?
- Will the uncertainty on the pinching compromise the determination of key properties?
- What is the impact of including other detection channels?
- What can we infer on the neutron star properties?

1. FLUX RECONSTRUCTION AND *M*–*R* RELATION OF THE NEUTRON STAR

- Monte Carlo based likelihood analyses
- Without usual assumptions
- Shape α unknown
- Three detection channels (9 d.o.f.)
    - $\overline{\nu}_e + p \to e^+ + n$ (IBD)
    - $\nu + e^- \to \nu + e^-$ (ES)
    - $\nu + {}^{16}O \to \nu + X + \gamma$ (OS)

REFERENCE PAPERS

- A. Gallo Rosso, F. Vissani, M.C. Volpe, JCAP 1711 (2017) no.11, 036
- A. Gallo Rosso, F. Vissani, M.C. Volpe, JCAP 1804 (2018) no.04, 040

2. LATE-TIME SIGNAL AND PROTO-NEUTRON STAR RADIUS

- First analysis of its kind
- Neutrino signal alone
- Reference model
- Exploration of extended theories of gravity

REFERENCE PAPER

- A. Gallo Rosso, S. Abbar, F. Vissani, M.C. Volpe, JCAP 1812 (2018) no.12, 006

1. Flux reconstruction

1. Flux reconstruction

Hypotheses and method

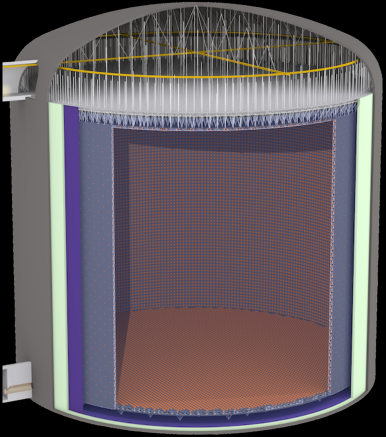
Hypotheses and method

SUPERNOVA PARAMETERS

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

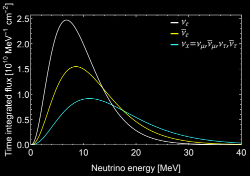
DETECTORS

- Super-Kamiokande
  - 22.5 kton (fiducial mass)
- Hyper-Kamiokande
  - 374 kton (fiducial mass)
- 5 MeV threshold
- 100% efficiency



Hypotheses and method

TIME-INTEGRATED FLUXES (FLUENCES)



- Quasi-thermal alpha-fit [4]
  - 3 neutrino species (ν_e, $\overline{\nu}_\mathrm{e}$, ν_x)
  - 3 parameters ($\mathcal{E}$, $\langle E \rangle$, α)

$$\frac{\mathrm{d}\,F_i^0}{\mathrm{d}\,E_\nu} = \frac{\mathcal{E}_i}{4\pi D^2} \frac{(\alpha_i+1)^{(\alpha_i+1)}}{\Gamma(\alpha_i+1)} \frac{E^{\alpha_i}}{\langle E_i \rangle^{\alpha_i+2}} \exp\left[-(\alpha_i+1)\frac{E}{\langle E_i \rangle}\right]$$

- Agreement with SN 1987A data
- Good description of simulations

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[4] M.T. Keil et al., Astrophys. J. 590 (2003).

Hypotheses and method

NEUTRINO FLAVOR TRANSFORMATIONS IN SUPERNOVAE

- Normal mass hierarchy
- Mikheyev-Smirnov-Wolfenstein (MSW) effect

$$\begin{cases} F_{\nu_\mathrm{e}} = F_x^0 \\ F_{\overline{\nu}_\mathrm{e}} = |U_{e1}|^2 \cdot F_{\overline{\nu}_\mathrm{e}}^0 + (1 - |U_{e1}|^2) \cdot F_x^0 \end{cases}$$

- Neutrino self-interaction neglected

Hypotheses and method

TOTAL ENERGIES

- $\mathcal{E}_i^* = 0.5 \times 10^{53}$ erg

MEAN ENERGIES

- $\langle E_{\nu_e} \rangle^* = 9.5\,\mathrm{MeV}$
- $\langle E_{\overline{\nu}_e} \rangle^* = 12\,\mathrm{MeV}$
- $\langle E_{\nu_x} \rangle^* = 15.6\,\mathrm{MeV}$

PINCHING PARAMETERS

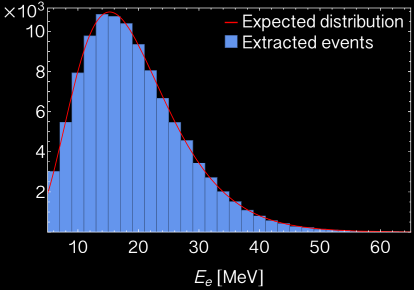
- $\alpha_i^* = 2.5$

C. Lujan-Peschard et al., JCAP (2014).

Teun Hocks, *Measuring*

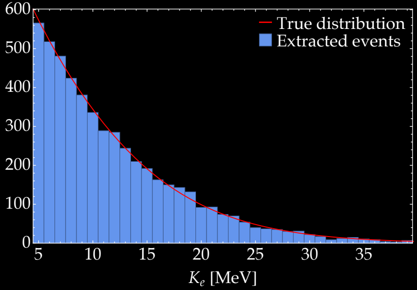
Hypotheses and method

— HYPER-KAMIOKANDE EXTRACTED EVENTS —



$\overline{\nu}_e + p \to e^+ + n$

(76 × 10^3 expected events)



$\nu + e^- \to \nu + e^-$

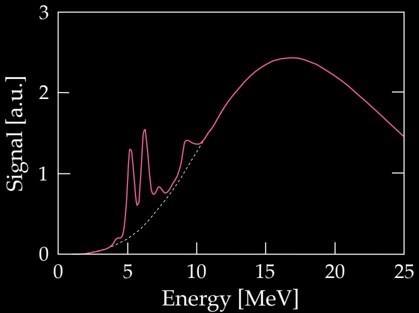
(4 × 10^3 expected events)

Hypotheses and method

$\nu + {}^{16}\mathrm{O} \rightarrow \nu + \mathrm{X} + \gamma$

- γ within $(4 \div 9)$ MeV
  - $\sim$ 800 OS
  - $\sim$ 8000 IBD+ES
- Non-Gaussian smearing
- No disentangling IBD+ES
- Neutral-Current Region

  $\hookrightarrow$ NCR = IBD + ES + OS



K. Langanke et al., Phys. Rev. Lett. 76 (1996).

Hypotheses and method

NEUTRINO-OXYGEN CROSS SECTION

$$\sigma_{OS}(E_\nu) \approx \kappa \cdot \sigma_0 \cdot (E_\nu/\mathrm{MeV} - 15)^4$$ [5]

- measurements expected [6]
- 10% uncertainty (optimistic)
- Systematic $\sim$ Gauss($\kappa^* = 1$, $\sigma_\kappa = 0.1$)
- Results weakly concerned

$\Bigg\}$ 10th parameter κ

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[5] J.F. Beacom and P. Vogel, PRD 58 (1998) 053010.

[6] K. Scholberg, talk at CNNP2017.

Hypotheses and method

LIKELIHOODS

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

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

3 ANALYSES

$$\text{IBD} \rightarrow \mathcal{L} = \mathcal{L}_{\text{IBD}}$$

$$\text{IBD + ES} \rightarrow \mathcal{L} = \mathcal{L}_{\text{IBD}} \times \mathcal{L}_{\text{ES}}$$

$$\text{IBD + ES + NCR} \rightarrow \mathcal{L} = \mathcal{L}_{\text{IBD}} \times \mathcal{L}_{\text{ES}} \times \mathcal{L}_{\text{NCR}}$$

R. Laha and J.F. Beacom, Phys. Rev. D89 (2014).

Hypotheses and method

PRIOR

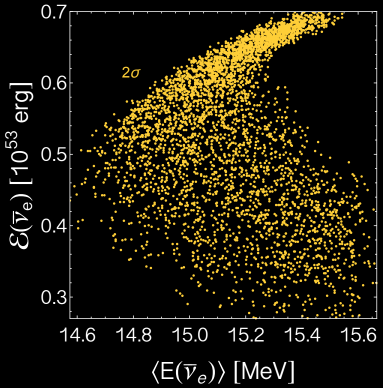
$$\begin{aligned} 0.2 \times 10^{53}\,\text{erg} \leq & \quad \mathcal{E}_i \quad \leq 1.0 \times 10^{53}\,\text{erg} \\ 5.0\,\text{MeV} \leq & \ \langle E_i \rangle \ \leq 30\,\text{MeV} \\ 1.5 \leq & \quad \alpha_i \quad \leq 3.5 \\ 0.8 \leq & \quad \kappa \quad \leq 1.2 \end{aligned}$$

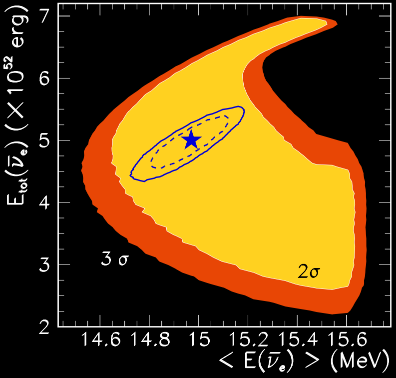
CONDITION

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

Hypotheses and method

Comparison with Minakata et al. (2008): Good agreement





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

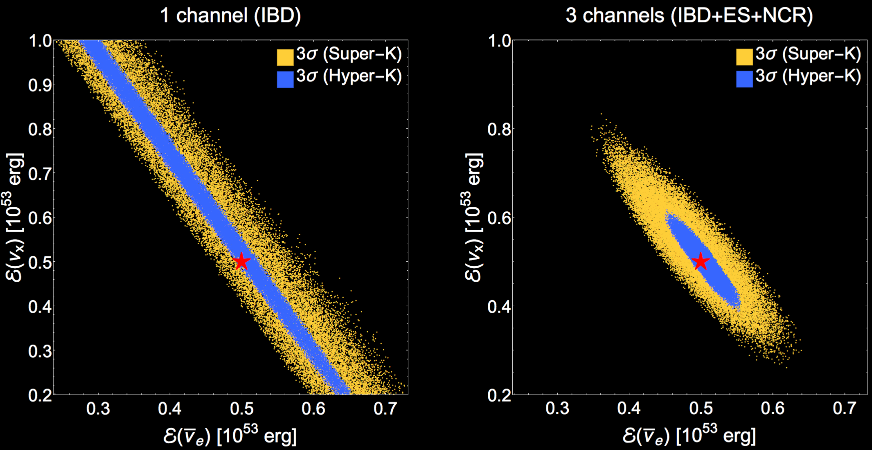
1. Flux reconstruction

Results on neutrino fluxes

Results on neutrino fluxes

— THE IMPORTANCE OF MANY DETECTION CHANNELS —

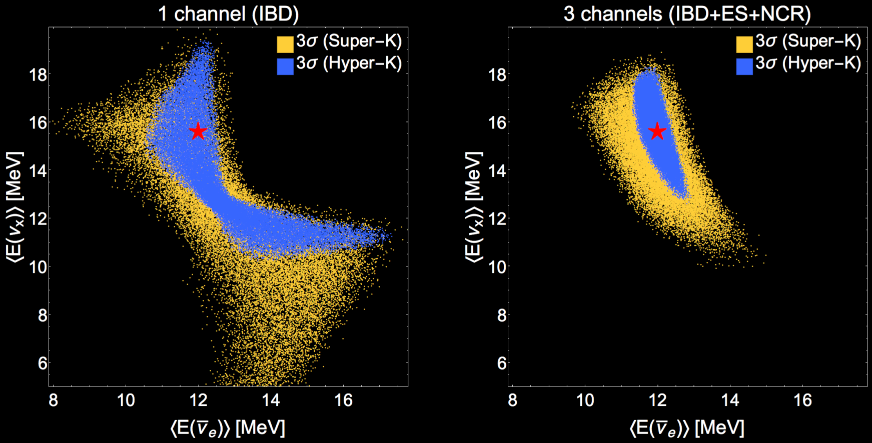
Degeneracy broken for $\overline{\nu}_e$ and ν_x total energies



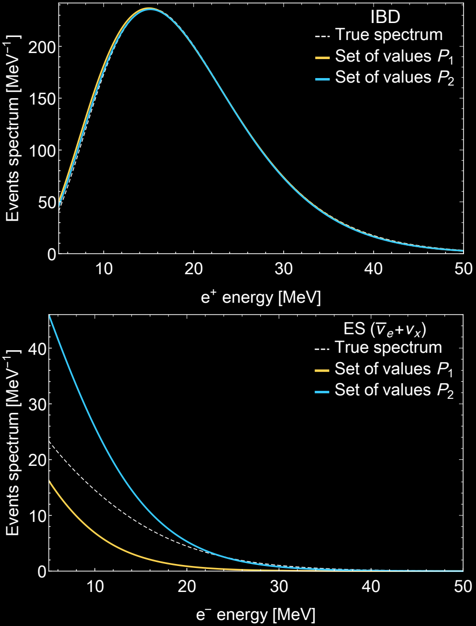
Results on neutrino fluxes

— THE IMPORTANCE OF MANY DETECTION CHANNELS —

Degeneracy broken for $\overline{\nu}_e$ and ν_x mean energies



Results on neutrino fluxes

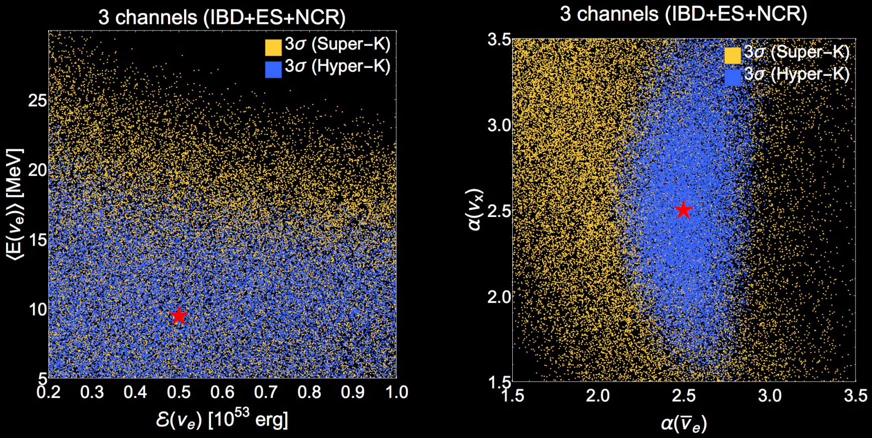


	P_1	P_2
$\mathcal{E}(\overline{\nu}_e)$ [10^{52}erg]	6.65	2.94
$\mathcal{E}(\nu_x)$ [10^{52}erg]	2	10
$\langle E(\overline{\nu}_e)\rangle$ [MeV]	12.8	13.5
$\langle E(\nu_x)\rangle$ [MeV]	9.3	11.9
$\alpha(\overline{\nu}_e)$	2.08	2.08
$\alpha(\nu_x)$	2.16	2.16

Results on neutrino fluxes

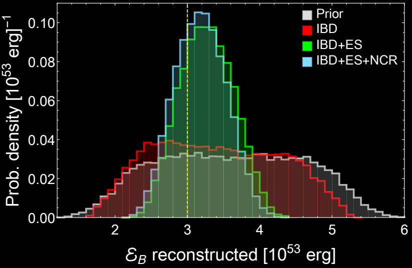
— STILL SOME RESIDUAL UNCERTAINTIES —

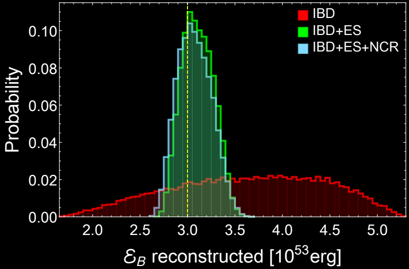
ν_e species undetermined and almost all pinching parameters α



Gravitational binding energy of the neutron star

— TOTAL NEUTRINO EMITTED ENERGY —





$\mathcal{E}_B$	[10^{53} erg]	Acc. %
IBD	3.40 ± 0.86	25.1
IBD+ES	3.27 ± 0.37	11.2
IBD+ES+NCR	3.18 ± 0.35	11.0

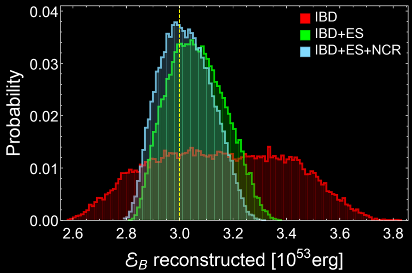
Super-Kamiokande

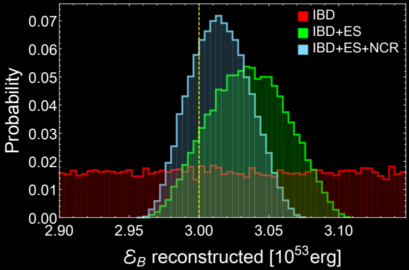
$\mathcal{E}_B$	[10^{53} erg]	Acc. %
IBD	3.64 ± 0.79	21.7
IBD+ES	3.10 ± 0.16	5.3
IBD+ES+NCR	3.07 ± 0.18	5.8

Hyper-Kamiokande

Gravitational binding energy of the neutron star

— TOTAL NEUTRINO EMITTED ENERGY IN EQUIPARTITION ($\mathcal{E}_{\text{tot}} = \mathcal{E}_i/6$) —





$\mathcal{E}_B$	[10^{53} erg]		Acc. %
IBD	3.15	$\pm$ 0.25	7.9
IBD+ES	3.06	$\pm$ 0.10	3.4
IBD+ES+NCR	3.023	$\pm$ 0.095	3.1

Super-Kamiokande

$\mathcal{E}_B$	[10^{53} erg]		Acc. %
IBD	3.13	$\pm$ 0.23	7.4
IBD+ES	3.130	$\pm$ 3.035	0.89
IBD+ES+NCR	3.015	$\pm$ 0.021	0.68

Hyper-Kamiokande

1. Flux reconstruction

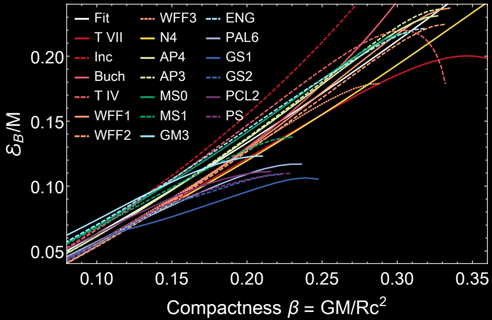
Results on mass–radius relation

Mass–radius relation of the neutron-star

EQUATION OF STATE [7]

$$\frac{(0.60 \pm 0.05)\beta}{1 - \beta/2} = \frac{\mathcal{E}_B}{Mc^2}$$

- Relation $\mathcal{E}_B$–β
    - $\beta = GM/Rc^2$
    - $\mathcal{E}_B \approx \mathcal{E}_{\text{tot}}$
- 10% uncertainty



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[7] J. M. Lattimer and M. Prakash, Phys. Rept. 442 (2007) 109.

Neutron star

$$M = \sqrt{\frac{\mathcal{E}_B R}{0.6\,G}}\left[\sqrt{1+\epsilon^2}-\epsilon\right] \quad \text{with} \quad \epsilon = \frac{1}{4}\sqrt{\frac{\mathcal{E}_B G}{0.6\,R\,c^4}}$$

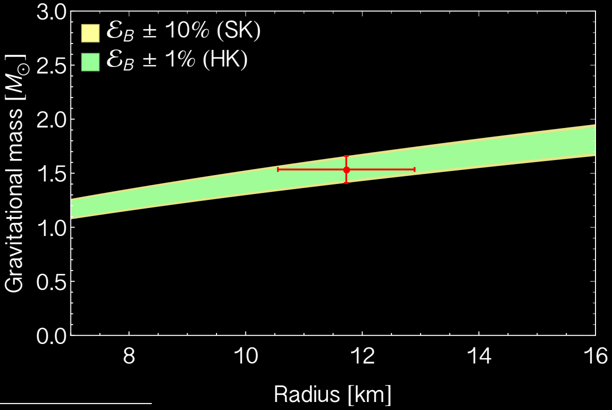
Total energy $\mathcal{E}_{tot}$

$+$

Equation of state

$\Downarrow$

M–R constraint[8]



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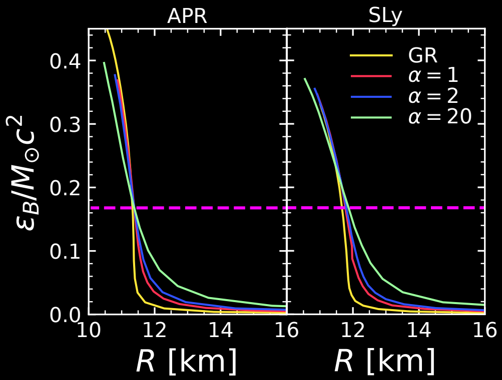
[8] An estimation of the baryonic mass may also be needed.

2. Late time signal and *R* of PNS

$\mathcal{E}_B$–R relation

Solving Tolman-Oppenheimer-Volkoff (TOV) equations

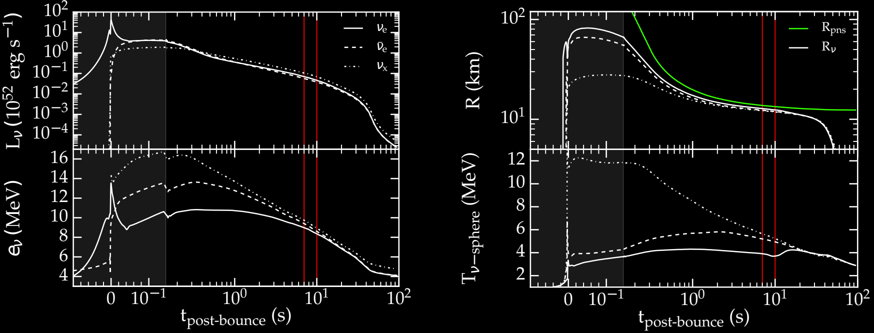
Standard and $f(\mathcal{R})$ gravity: Ricci scalar $\mathcal{R} \to f(\mathcal{R}) = \mathcal{R} + \alpha_G \mathcal{R}^2$



— SENSITIVE TO EoS AND POTENTIALLY TO EXTENDED GR —

Reference model for neutrino signal

— QUASI-STATIC COOLING (6 ÷ 10 s window) —



Almost constant behavior

L.F. Roberts and S. Reddy (2017) arXiv:1612.03860.

Proto-neutron star radius reconstruction

FERMI-DIRAC BLACK BODY

Pinching parameter $\eta(\alpha)$

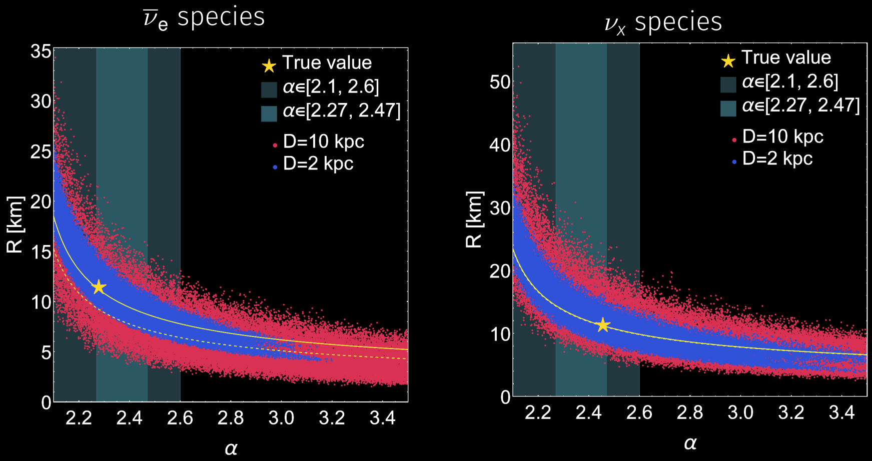
$$L = -\frac{24\pi^2 c}{(hc)^3}\,\mathrm{Li}_4(-e^\eta)\,R^2\left[\frac{\langle E\rangle\,F_2(\eta)}{F_3(\eta)}\right]^4$$

RADIUS RECONSTRUCTION

- Measuring $(L,\,\langle E\rangle,\,\eta)$ to get R
- Hyper-Kamiokande
- $6 \div 10\,\mathrm{s}$ window ⇒ theoretically clean but smaller dataset
    - 10 kpc ⇒ # events as Super-Kamiokande in previous project
    - 2 kpc ⇒ # events as Hyper-Kamiokande in previous project

Proto-neutron star radius reconstruction

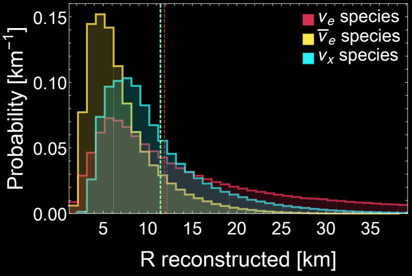
— CORRELATION BETWEEN R AND α —



$$L \propto \mathrm{Li}_4\left(-e^{\eta(\alpha)}\right)\frac{F_2[\eta(\alpha)]}{F_3[\eta(\alpha)]}$$

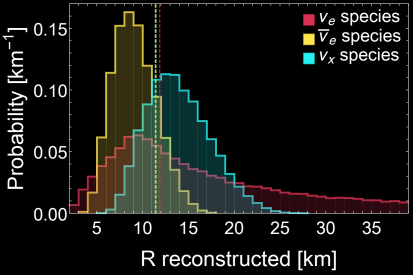
Proto-neutron star radius reconstruction

— RADII RECONSTRUCTED @ 10 kpc —



R	R^* [km]	Rec. [km]	%
ν_e	11.9	19 ± 19	100
$\overline{\nu}_e$	11.5	7 ± 4	56
ν_x	11.4	11 ± 6	55

Default $\alpha \in [2.1, 3.5]$

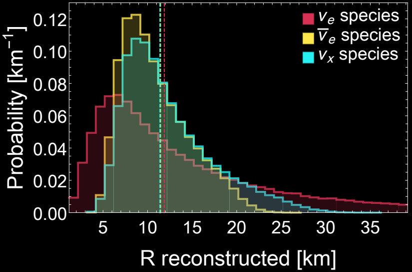


R	R^* [km]	Rec. [km]	%
ν_e	11.9	24 ± 21	86
$\overline{\nu}_e$	11.5	9 ± 2	26
ν_x	11.4	14 ± 3	25

Tighter $\alpha \in [2.27, 2.47]$

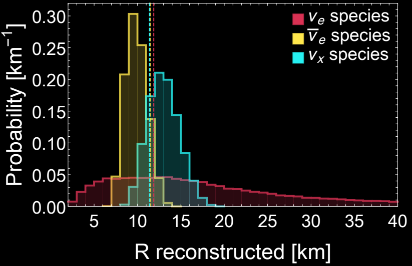
Proto-neutron star radius reconstruction

— RADII RECONSTRUCTED @ 2 kpc —



R	R^* [km]	Rec. [km]	%
ν_e	11.9	17 ± 16	97
$\overline{\nu}_\mathrm{e}$	11.5	11 ± 4	34
ν_x	11.4	12 ± 5	40

Default $\alpha \in [2.1, 3.5]$



R	R^* [km]	Rec. [km]	%
ν_e	11.9	22 ± 18	81
$\overline{\nu}_\mathrm{e}$	11.5	10 ± 1	12
ν_x	11.4	13 ± 2	14

Tighter $\alpha \in [2.27, 2.47]$

Inverting the perspective

USING R TO CONSTRAIN α

- Realistic values
  - $R \in [8, 16]$ km from the EoS
  - $\alpha(\bar{\nu}_e)$ from $\sim 14\%$ to ~ 5–7% @ 2–10 kpc
- 10% accuracy
  - $R \in [10.2, 13.1]$ km
  - $\alpha(\bar{\nu}_e)$ from $\sim 14\%$ to ~ 1–2% @ 2–10 kpc

Conclusions and perspectives

Conclusions

1. NEUTRINO FLUX RECONSTRUCTION

- Large datasets necessary but not sufficient
- Elastic scattering is crucial to break the degeneracy
- Hyper-Kamiokande
    - $\mathcal{E}_B$ with few %
    - $\overline{\nu}_\mathrm{e}$ well determined ($\langle E \rangle, \alpha \sim$ %)
    - ν_e undetermined: prior constraint
- NS mass at $\sim 30\%$ for R known at $\sim 10\%$

Conclusions

2. LATE-TIME ANALYSIS

- *R* sensitive to EoS and gravity
- Radius determination from black body emission
- *R*–α strong correlation
  - Poor accuracy if α is not strongly constrained
- Pinching α constrained from physical values of *R*

Perspectives

DEVELOPMENTS AND IMPROVEMENTS

- Flavor conversion phenomena:
    - Neutrino self-interaction
- Experimental apparatus:
    - Improving detector response
- Likelihood analysis:
    - More detectors/channels
    - Determination of ν_e species