ICRR Workshop
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Future Detection of Supernova Neutrinos and Its Implications for Astroparticle Physics

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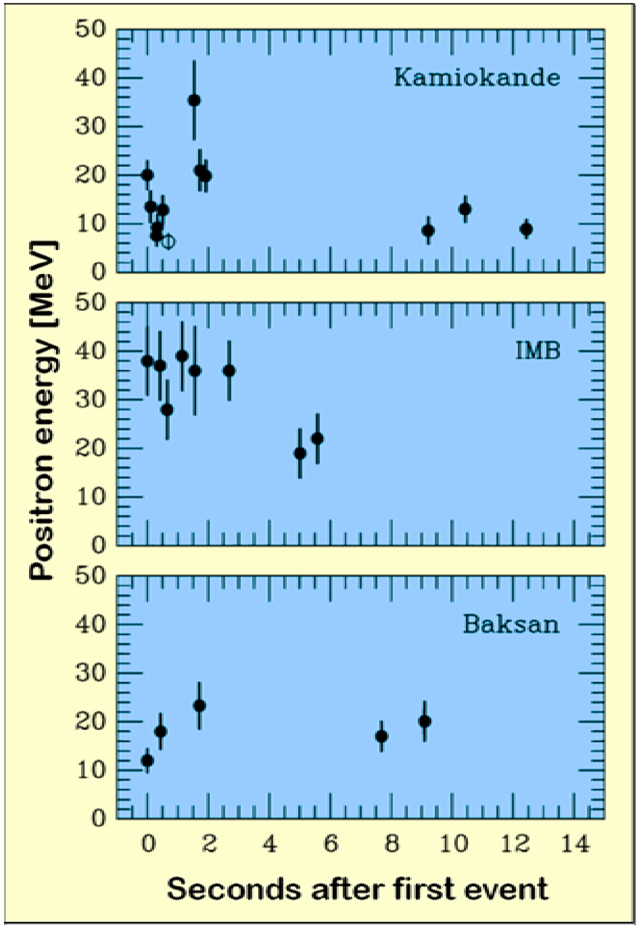
S. Ando & K. Sato, JCAP10(2003)001

S. Ando, ApJ in press (astro-ph/0401531)

INTRODUCTION

Birth of Neutrino Astronomy

- Neutrino burst from SN 1987A



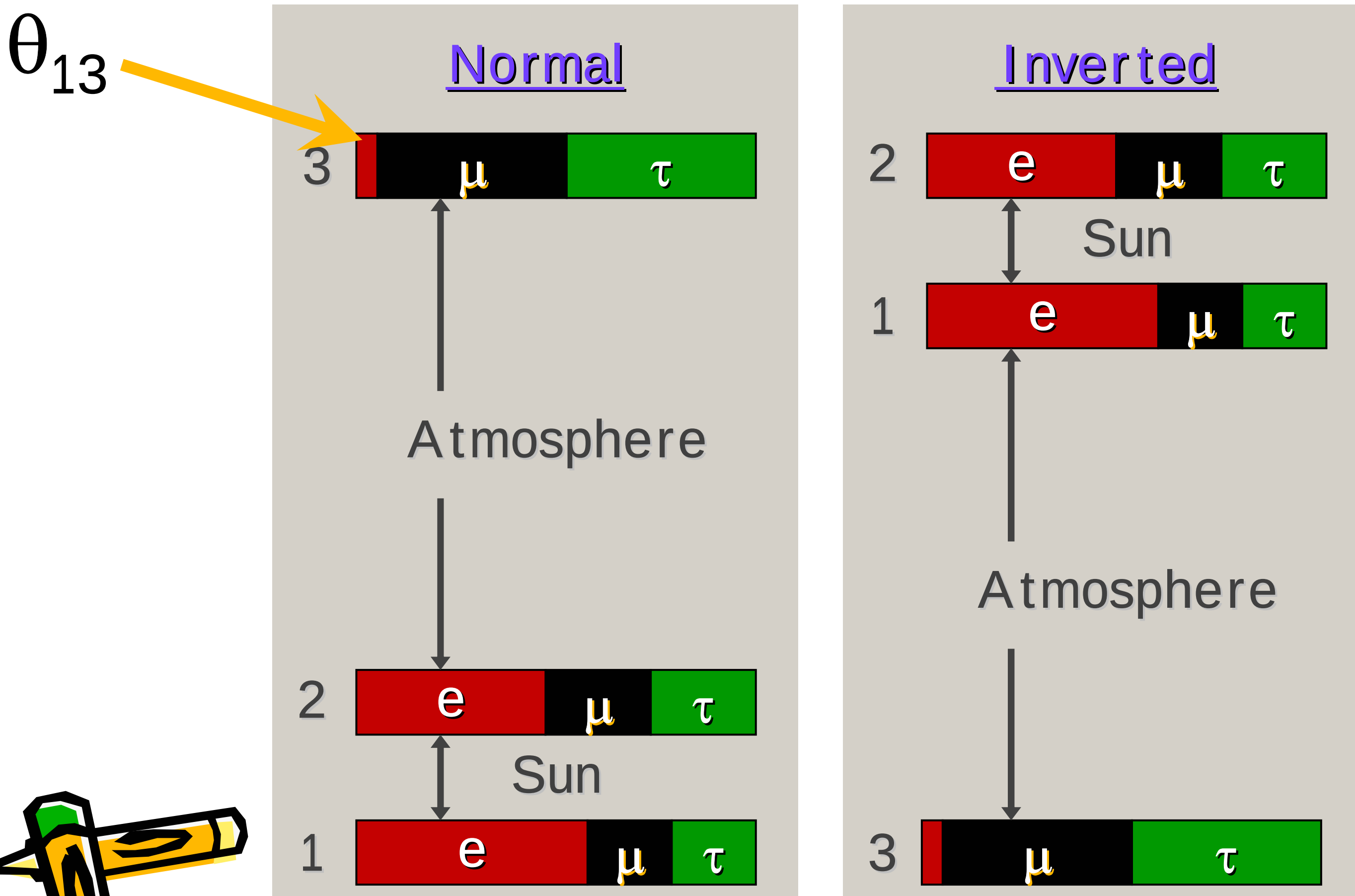
Neutrino Oscillation

- Atmospheric neutrinos (2-3 mixing)
  - Deficit of ν_μ ($\nu_\mu \rightarrow \nu_\tau$ oscillation)
  - $\Delta m_{13}^2 \sim 10^{-3}$ eV^2, $\theta_{23} \sim 45^o$ (maximal mixing)
- Solar/reactor neutrinos (1-2 mixing)
  - Deficit of ν_e ($\nu_e \rightarrow \nu_{\mu,\tau}$ oscillation)
  - $\Delta m_{12}^2 \sim 10^{-4}$ eV^2, $\theta_{12} \sim 30^o$ (bi-maximal mixing)

What comes next?

- **Particle Physics**
  - Mass hierarchy, θ_{13}, CP-phase
  - Absolute mass scale
  - Magnetic moment?, Decay??
- **Astrophysics and Cosmology**
  - Sun and the Earth via solar/geo-neutrinos
  - Galactic supernova neutrino burst
  - Relic supernova neutrinos

Mass Hierarchy & Theta_13



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Part I

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  - Absolute mass scale
  - Magnetic moment?, Decay??
- **Astrophysics and Cosmology**
  - Sun and the Earth via solar/geo-neutrinos
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  - Relic supernova neutrinos

Part I

Part II

Brief overview

Supernova Relic Neutrinos

- Diffuse background of past supernova neutrinos
- Flux and rate estimate
- Future detector performance
- Implications for cosmic star formation history

Supernova Neutrino Burst and Flavor Conversion

- Flavor conversion inside supernova envelope
- Neutrino magnetic moment with normal/inverted mass hierarchy
- Expected signal at Super-K detector and its implications

Part I

Supernova relic neutrinos and cosmic star formation history

1. Introduction
2. Formulation & Models
3. Results of Numerical Calculation
4. Future Detector Performance
5. Conclusions

Ando, Sato, & Totani, Astropart. Phys. **18** (2003) 307
Ando & Sato, Phys. Lett. B **559** (2003) 113
Ando, ApJ in press (astro-ph/0401531)

Part I

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Supernova relic neutrinos

Supernova Explosion

99% of its gravitational binding energy is released as neutrinos (supernova neutrino burst)

It is considered to trace the cosmic star formation rate (SFR).

There should be a diffuse background of neutrinos which were emitted from past supernova explosions.

<u>“Supernova Relic Neutrinos (SRN)”</u>

Motivations

- Is it really detectable?
  - Precise rate and background estimates are essential.
    - Kaplinghat, Steigman & Walker (2000); Ando, Sato & Totani (2003)
- Galaxy evolution and cosmic star formation rate
    - Totani, Sato & Yoshii (1996); Malaney (1997); Hartmann & Woosley (1997); Fukugita & Kawasaki (2003); Strigari et al. (2003); Ando (2004)
- Physics of supernova neutrinos
- Neutrino properties as an elementary particle
  - Neutrino oscillation
    - Ando & Sato (2003)
  - Neutrino decay (coupling with e.g. Majoron)
    - Ando (2003); Fogli et al. (2004)

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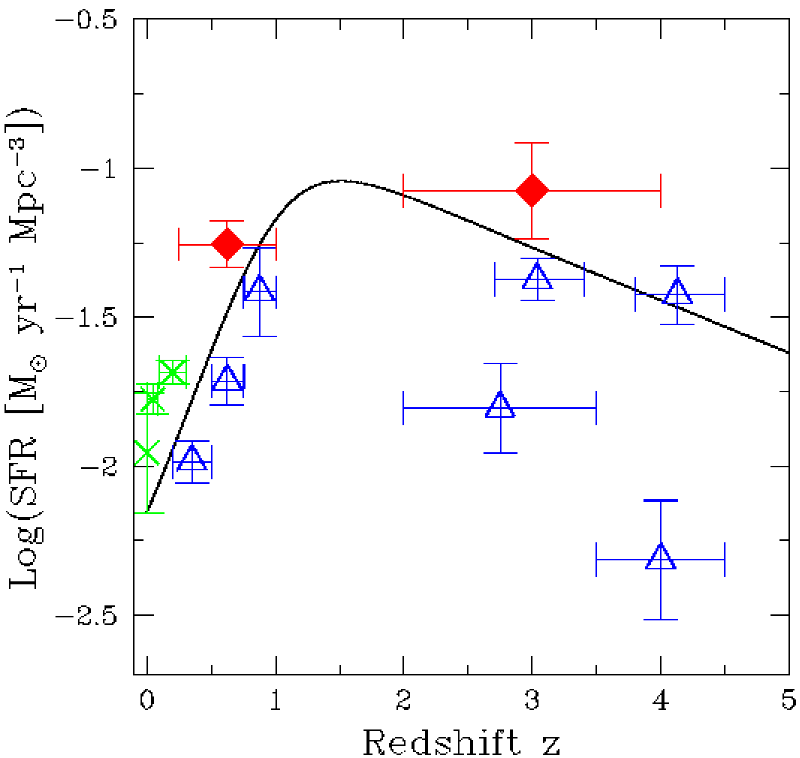
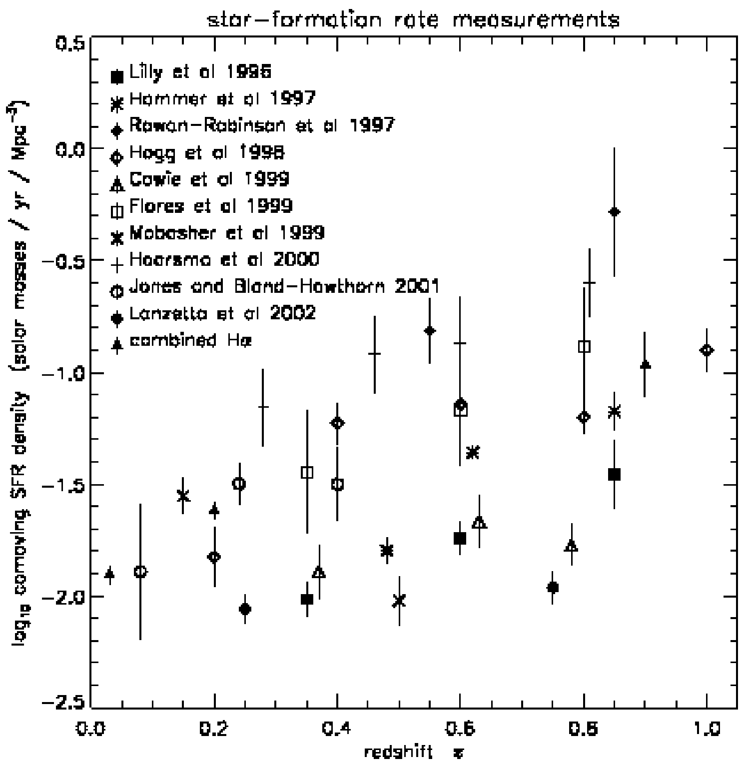
Cosmic star formation rate



- Cosmic SFR is inferred from UV, Hα, submm/FIR luminosity density.

Cosmic star formation rate



Hogg, astro-ph/0105280

- Cosmic SFR is inferred from UV, Hα, submm/FIR luminosity density.
- Although there seems to be a general trend at low-z, these estimates are quite uncertain!
- We deserve other independent methods.

SRN as an SFR indicator

UV luminosity density

- Advantages
  - Easier observation
  - Spectral features such as line/edge → enables redshift measurement
- Disadvantages
  - Dust extinction

SN relic neutrinos

- Advantages
  - Completely free from dust
  - Directly connected with the death of massive stars → good SFR tracer
- Disadvantages
  - Difficult!!
  - No spectral feature

But, the detection is within reach in the near future!!

Part I

Supernova relic neutrinos and cosmic star formation history

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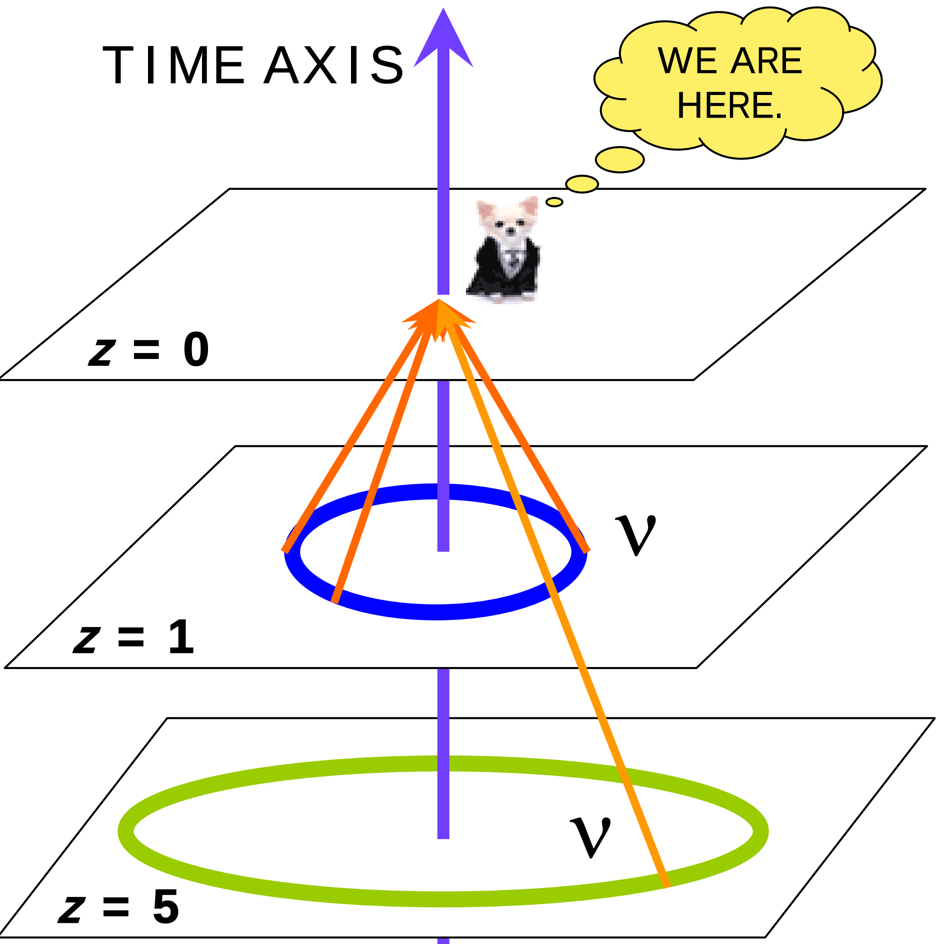
How to calculate the SRN flux

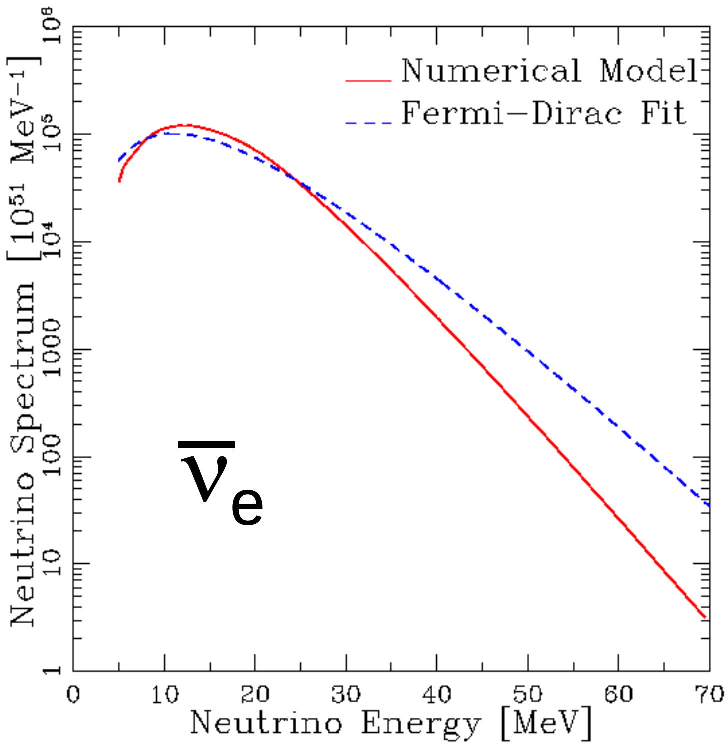


We need information concerning...

1. Neutrino spectrum emitted from each supernova explosion.
2. Neutrino oscillation within supernovae and the Earth.
3. Supernova rate.

$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\max}} R_{\rm SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

Original neutrino spectrum



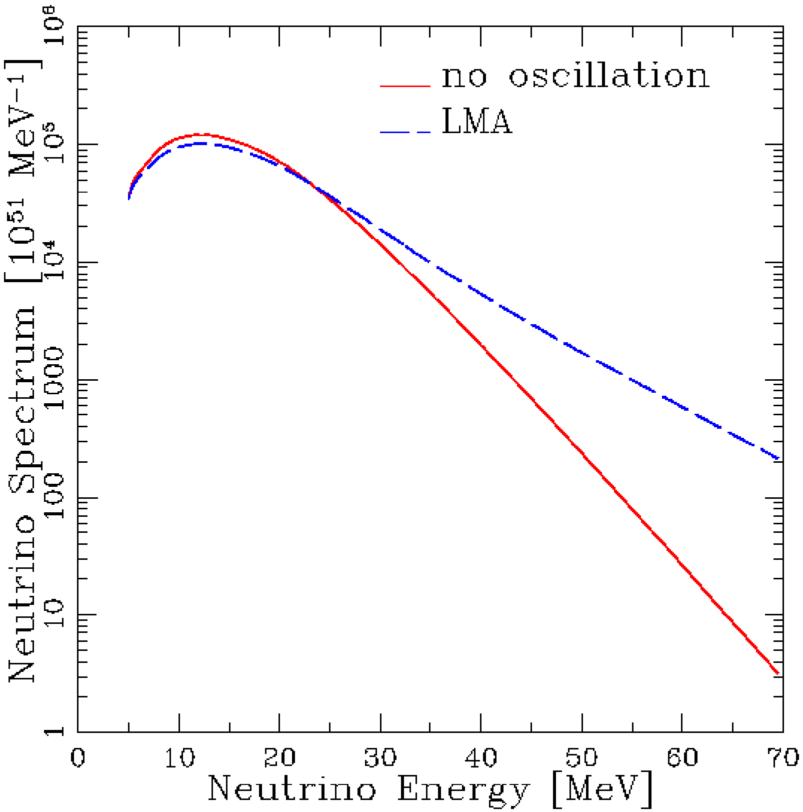
LL model of $20M_3$

- Neutrino spectra calculated numerically by three independent groups are adopted.
- Average energies (MeV)

Model	$\bar{\nu}_e$	ν_x	Ratio
LL	15.4	21.6	1.4
TBP	11.4	14.1	1.2
KRJ	15.4	15.7	1.0

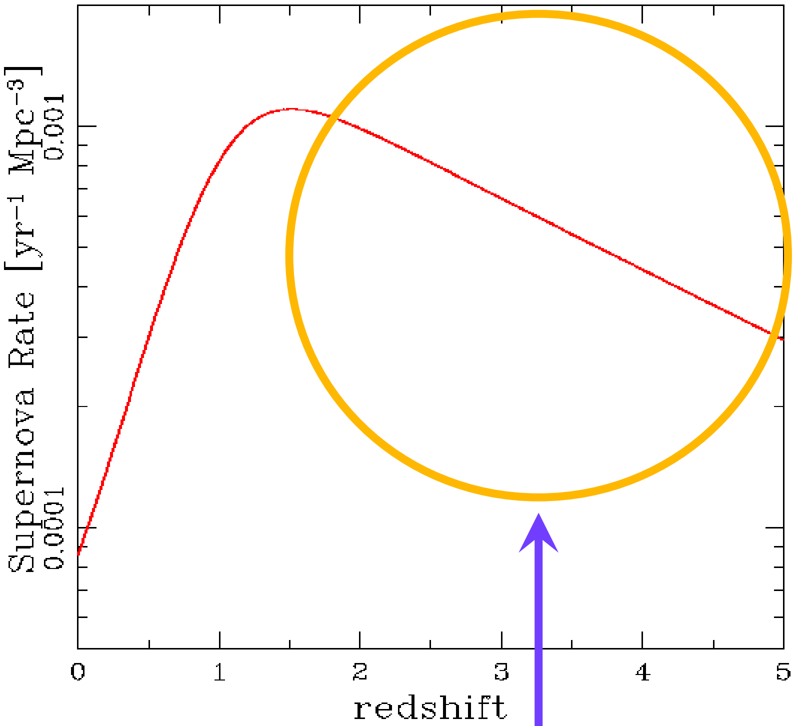
LL: Totani, Sato, Dalhed & Wilson (1998)
TBP: Thompson, Burrows & Pinto (2003)
KRJ: Keil, Janka & Raffelt (2003)

Spectrum after oscillation



- Here, we only consider the case of normal mass hierarchy without magnetic moment.
- In the case of large mixing, flavor conversion occurs efficiently (~30% mixing).
- The difference in average energies is essential.

Supernova rate history



- Supernova rate is inferred from SFR via

$$R_{\rm SN}(z) = \psi_*(z)\,\frac{\int_{8M_\odot}^{125M_\odot} dm\,\phi(m)}{\int_{0}^{125M_\odot} dm\,m\phi(m)}$$

- Behavior at high redshift contains substantial uncertainties.
- But, as shown later, high redshift behavior is found irrelevant.

The uncertainty around here is not important so much.

Part I

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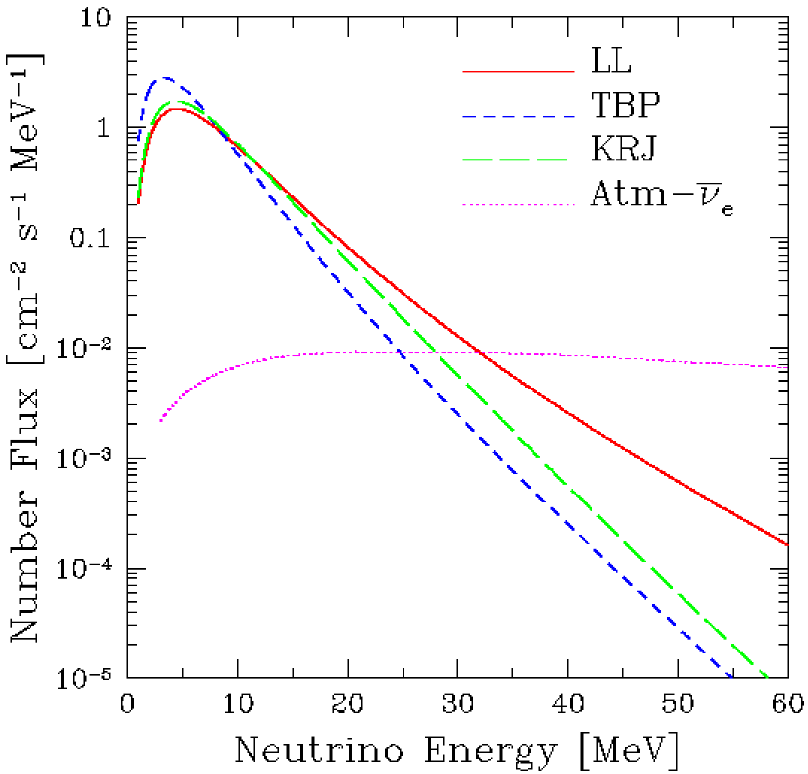
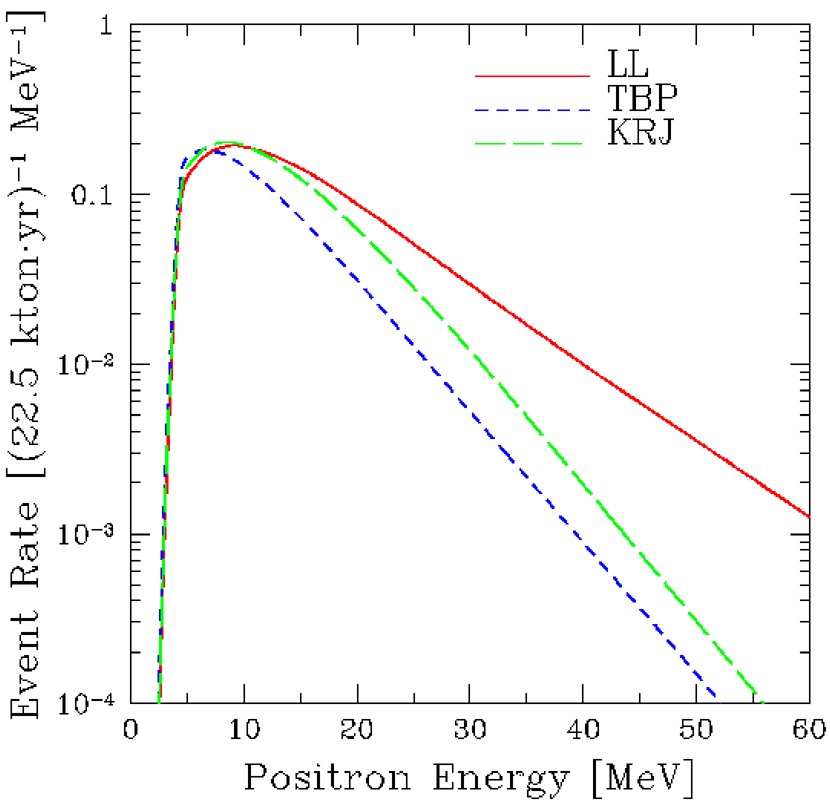
Flux & event rate



- Integrated flux (cm^{-2} s^{-1})

Model	E_ν > 11.3 MeV	E_ν > 19.3 MeV
LL	2.3	0.46
TBP	1.3	0.14
KRJ	2.0	0.28

Flux & event rate



- Integrated flux (cm^{-2} s^{-1})

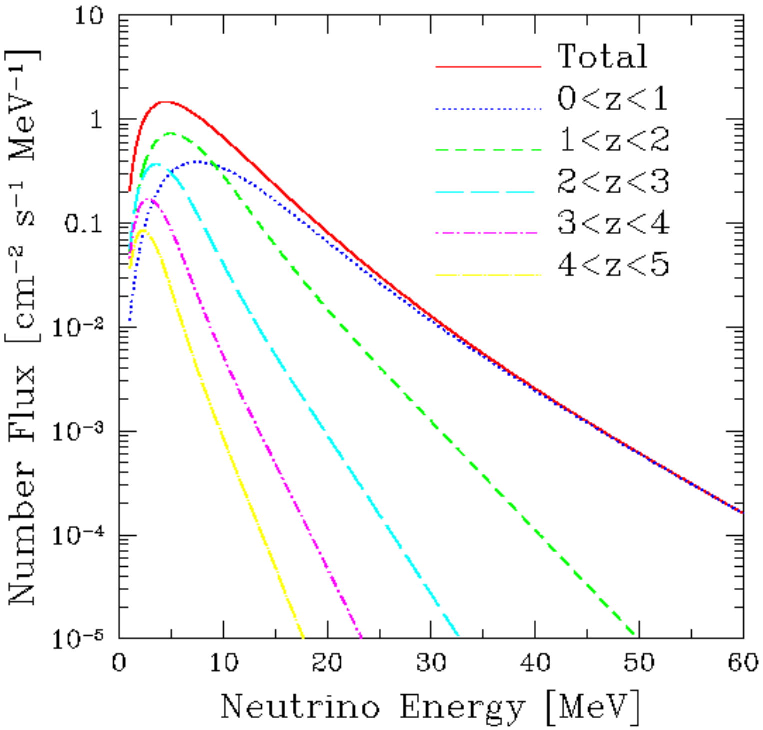
Model	$E_\nu > 11.3$ MeV	$E_\nu > 19.3$ MeV
LL	2.3	0.46
TBP	1.3	0.14
KRJ	2.0	0.28

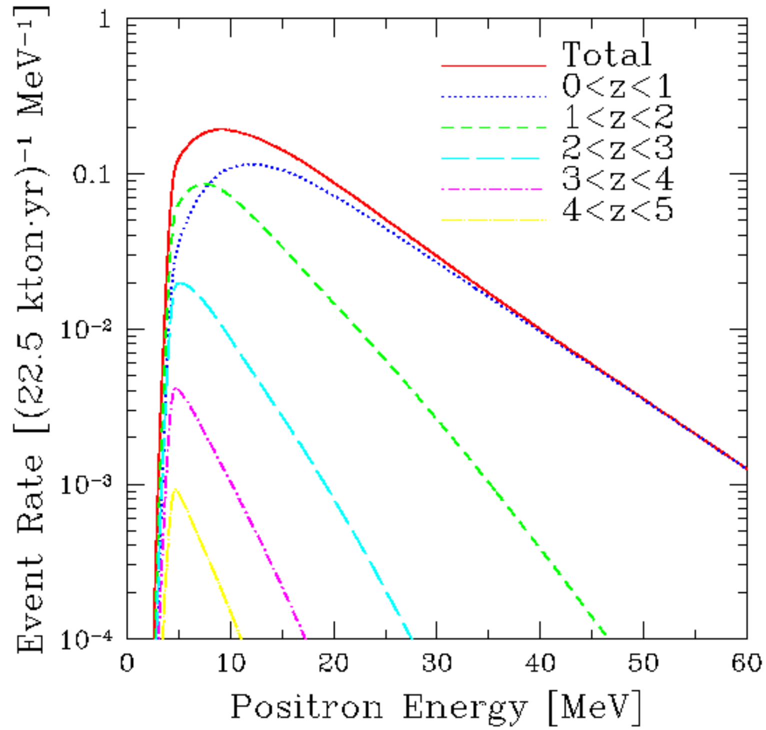
- Event rate at SK (yr^{-1})

Model	$E_e > 10$ MeV	$E_e > 18$ MeV
LL	2.3	1.0
TBP	0.97	0.25
KRJ	1.7	0.53

Flux & event rate (2)

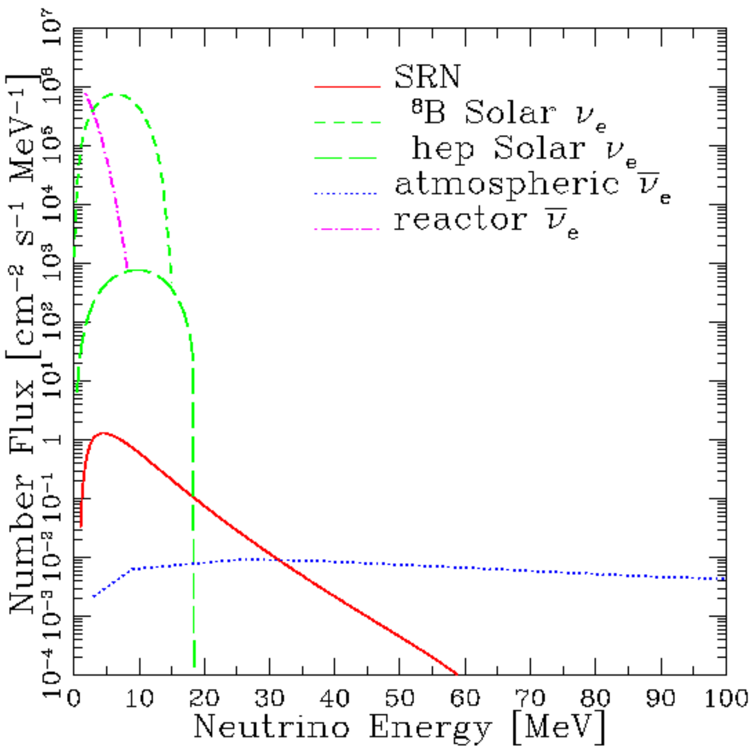
LL model

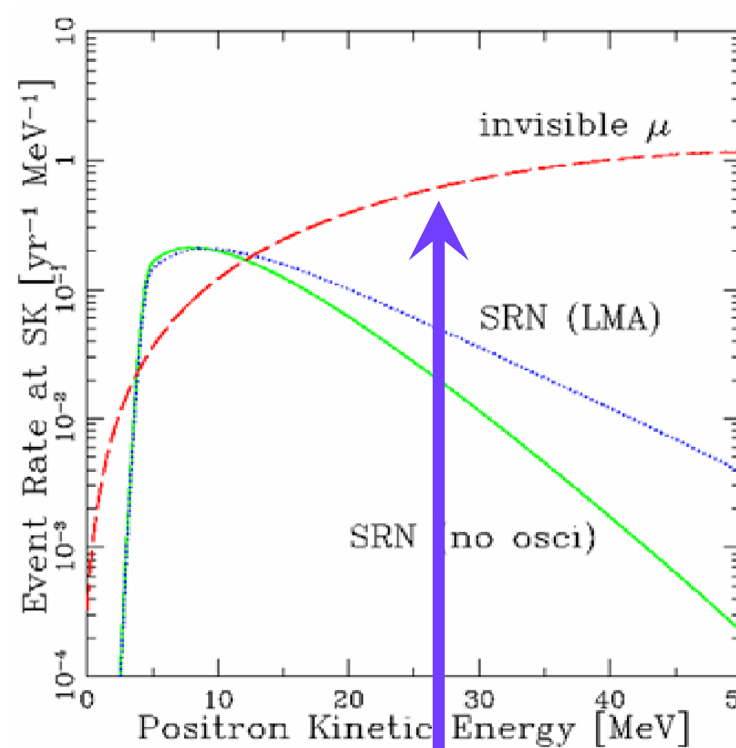




- At high energy region, high-z contribution is much less significant compared with local (z < 1) one.

Background events

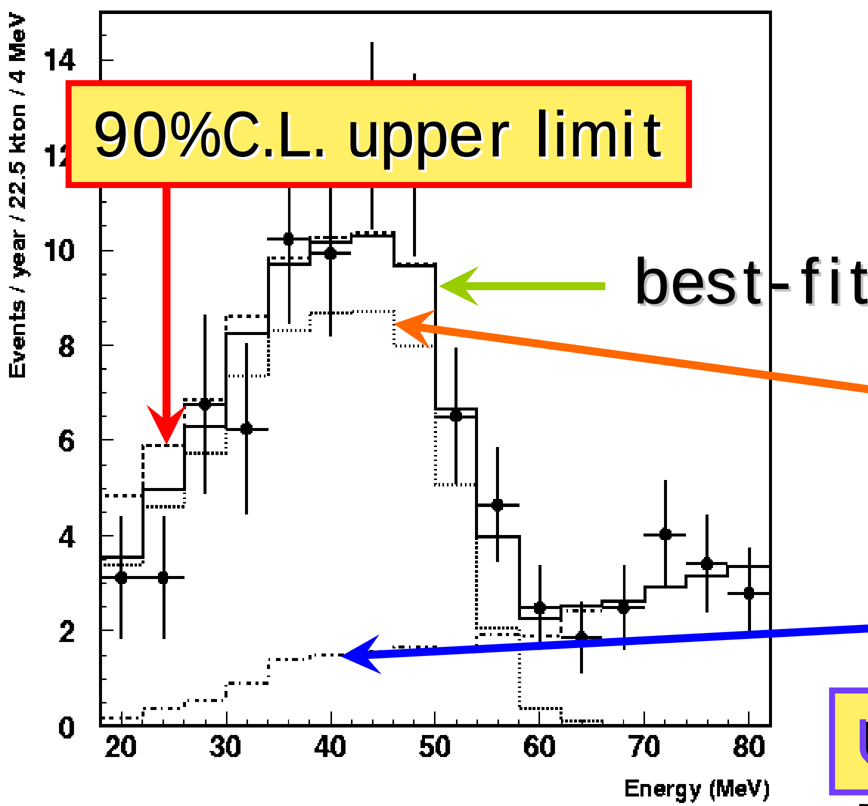




Atmospheric ν_μ → invisible μ → decay e

There is no "energy window."

Recent observational result from SK



Malek et al. (2003)

- Recently, SK Collaboration gave a very strong constraint on the SRN flux.

Atmospheric $\nu_\mu \rightarrow$ invisible $\mu \rightarrow$ decay e

Atmospheric $\bar{\nu}_e$

Upper limit for the LL model

Predicted flux	90% C.L. upper limit
12 cm^{-2} s^{-1}	31 cm^{-2} s^{-1}

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GADZOOKS!

GADZOOKS! Antineutrino Spectroscopy with Large Water Čerenkov Detectors

John F. Beacom[1] and Mark R. Vagins[2]

[1]*NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500*
[2]*Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, CA 92697*

(Dated: 25 September 2003)

We propose modifying large water Čerenkov detectors by the addition of 0.2% gadolinium trichloride, which is highly soluble, newly inexpensive, and transparent in solution. Since Gd has an enormous cross section for radiative neutron capture, with $\sum E_\gamma = 8$ MeV, this would make neutrons visible for the first time in such detectors, allowing antineutrino tagging by the coincidence detection reaction $\bar{\nu}_e + p \to e^+ + n$ (similarly for $\bar{\nu}_\mu$). Taking Super-Kamiokande as a working example, dramatic consequences for reactor neutrino measurements, first observation of the diffuse supernova neutrino background, Galactic supernova detection, and other topics are discussed.

PACS numbers: 95.55.Vj, 95.85.Ry, 14.60.Pq FERMILAB-Pub-03/249-A

- A proposal for water Cerenkov detectors (SK; Hyper-K; UNO, etc.) by Beacom & Vagins (hep-ph/0309300).

GADZOOKS!

A Quick Recap

Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!, or GADZOOKS!, is a Super–K upgrade being proposed by John Beacom and myself.

The basic idea is to use water-soluble gadolinium (tri)chloride, $GdCl_3$, to enable the detection of neutrons from the reaction

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

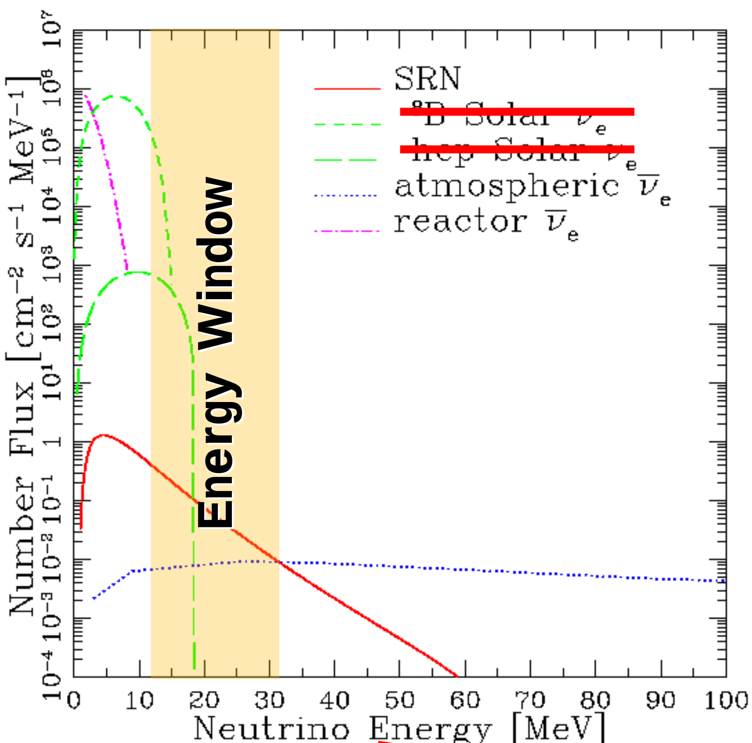
Among other things, this new capability will *greatly* enhance Super–K–III's response to supernova neutrinos (both relic and galactic), reactor $\bar{\nu}_e$'s, and $\bar{\nu}_e$'s from the Sun.

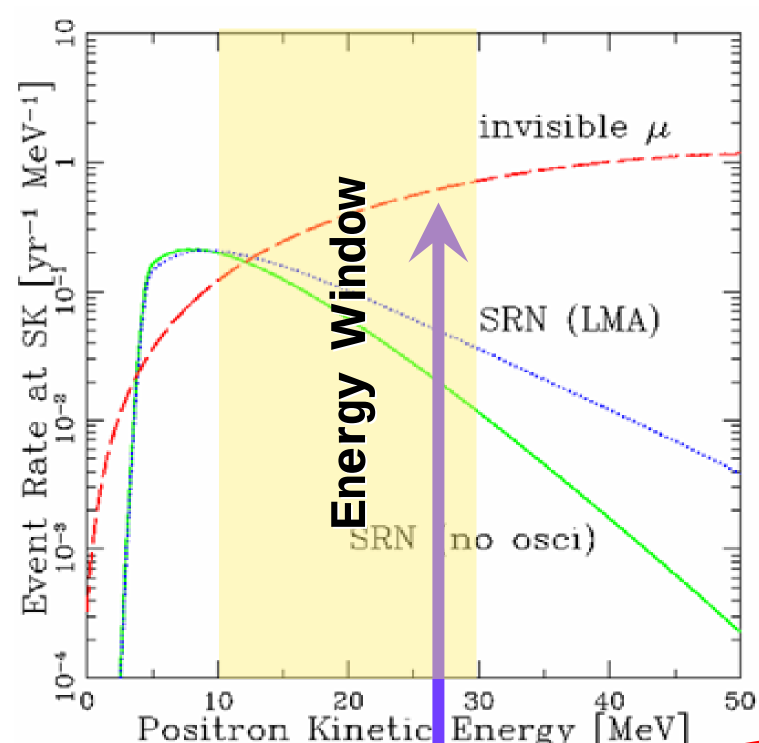
In order to collect >90% of these neutrons on gadolinium we'll only need to put *100 tons* of $GdCl_3$ in Super-K!

- Delayed coincidence signal of neutrons tagged by Gd.
- It enables to distinguish $\bar{\nu}_e$ from other flavors or μ-induced events.
- It opens up energy window at 10—30 MeV for the SRN detection.

M. Vagins@NOON2004

Energy window

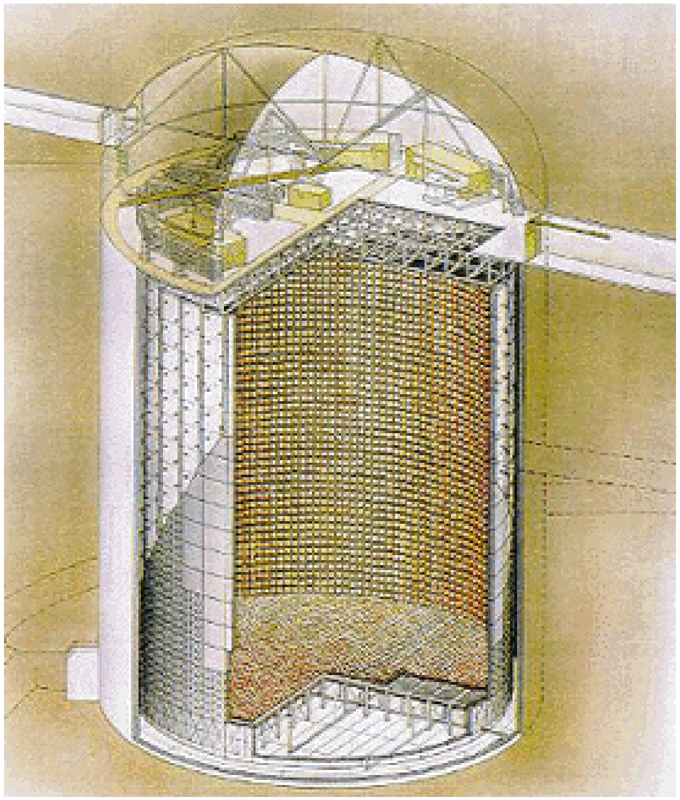


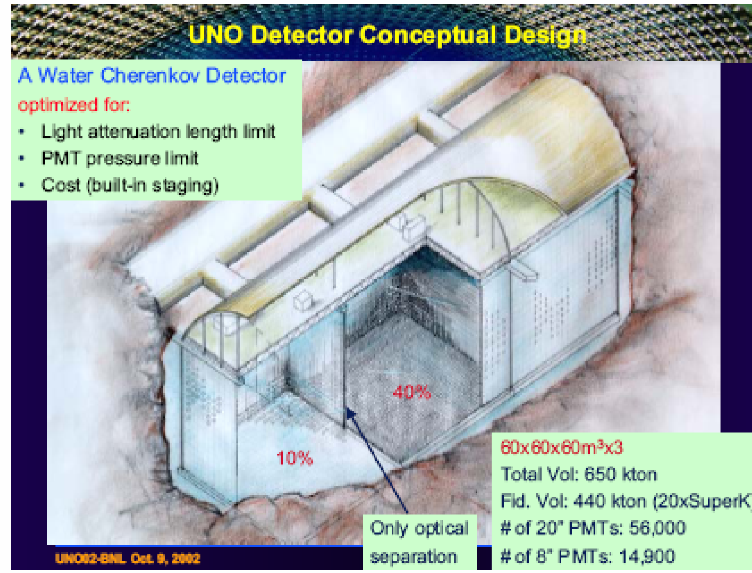


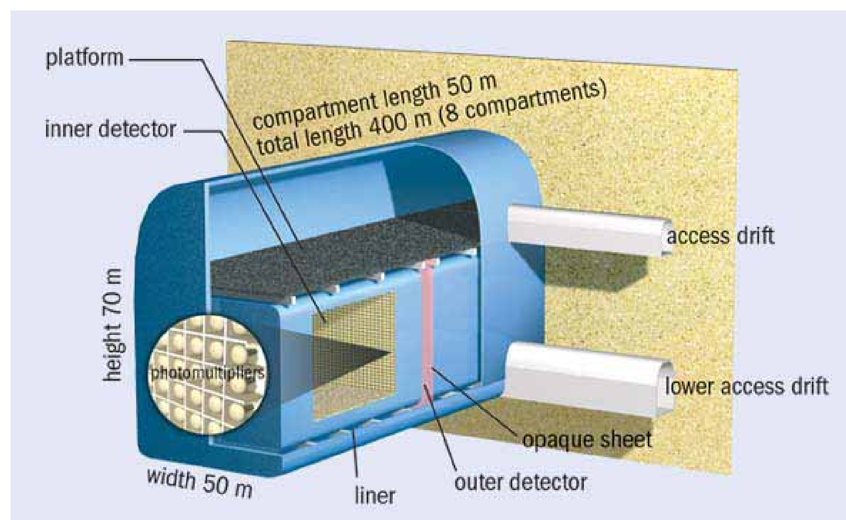
Atmospheric ν_μ → invisible μ → decay e

- Solar ν_e or invisible μ events become reducible!!

Upcoming detectors





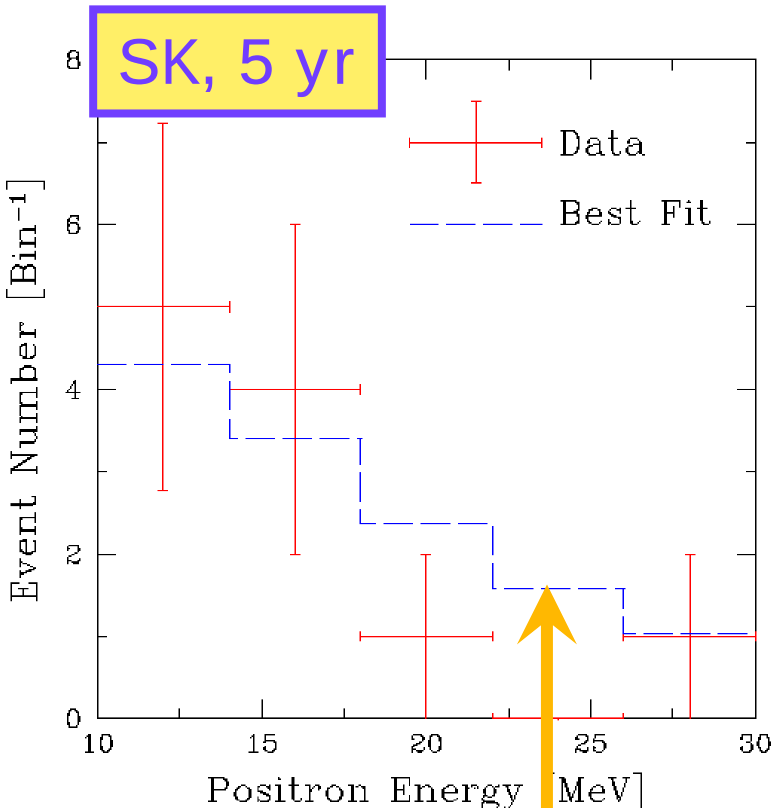


Monte Carlo simulation

Procedure

1. Simulate the SRN signal at 10—30 MeV
2. Analyze the simulated data with simple parameterization
3. Repeat the procedures 1. & 2., 1000 times
4. Obtain distribution of best fit values for adopted parameters

Simulated SRN data



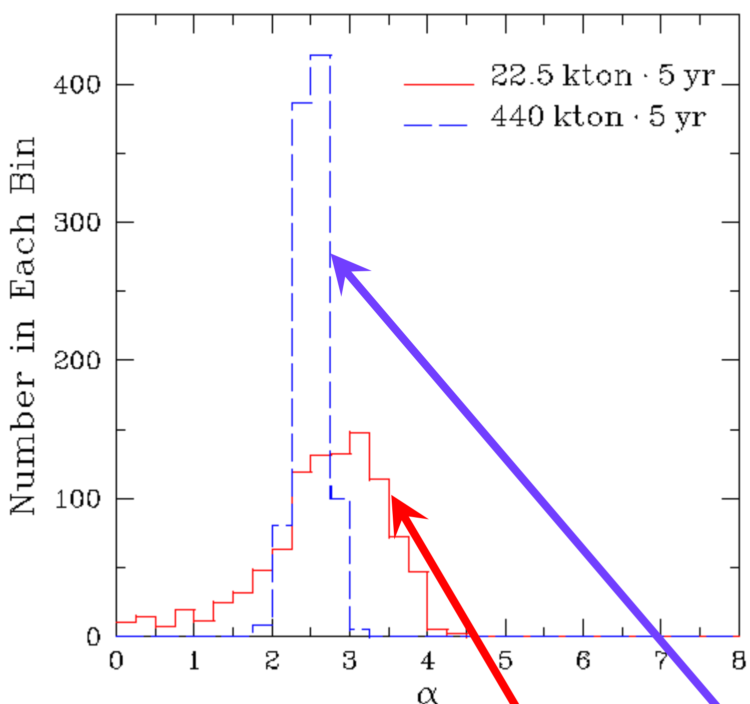
R_{SN}^0 : fixed
Best fit value: $\alpha = 3.0$

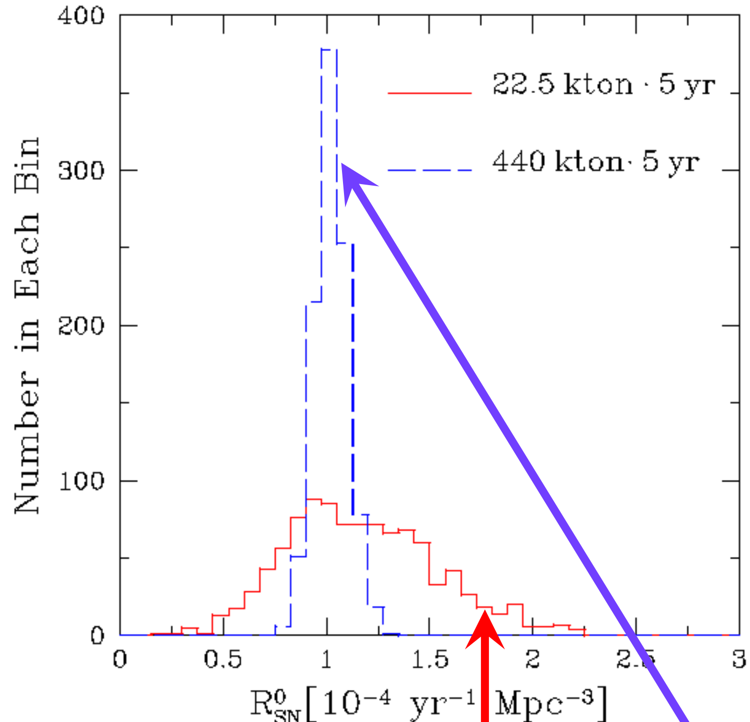
- Data are generated by MC simulation using the LL model.
- We analyze the data with two free parameters related to SN rate as,

$$R_{\rm SN}(z) = R_{\rm SN}^0 (1+z)^\alpha$$

- We assume that the supernova neutrino spectrum is quite well known.
  - Galactic SN will give us rich information.

Distribution of best fit parameters

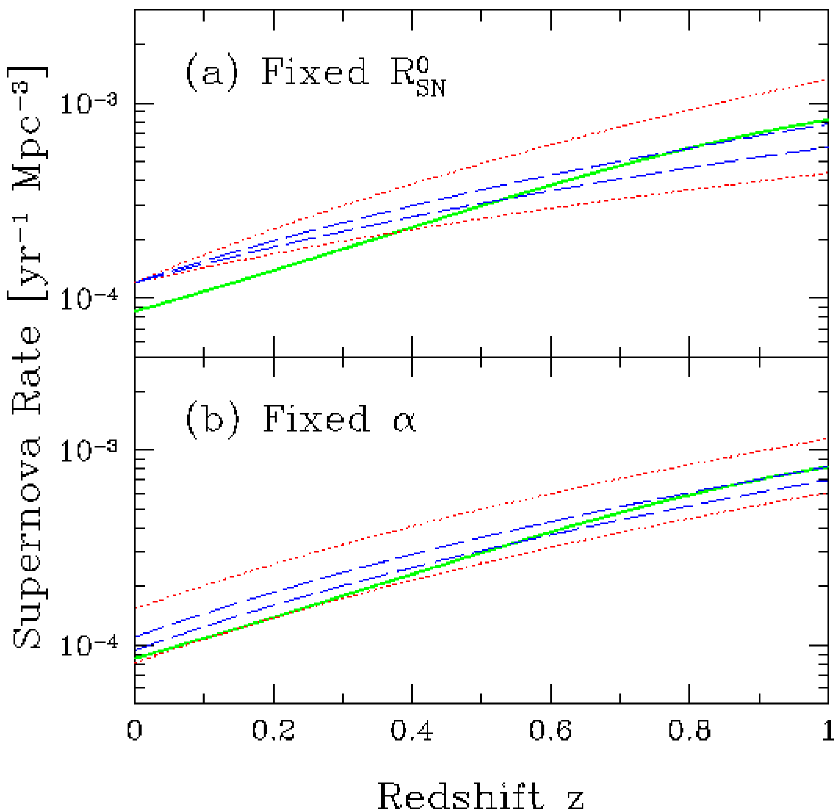




α = 2.7+/-0.8 (2.5+/-0.2);
Fixed $R_{SN}{}^0$ (1.2)

$R_{SN}{}^0$ = 1.2+/-0.4 (1.0+/-0.1);
Fixed α (2.9)

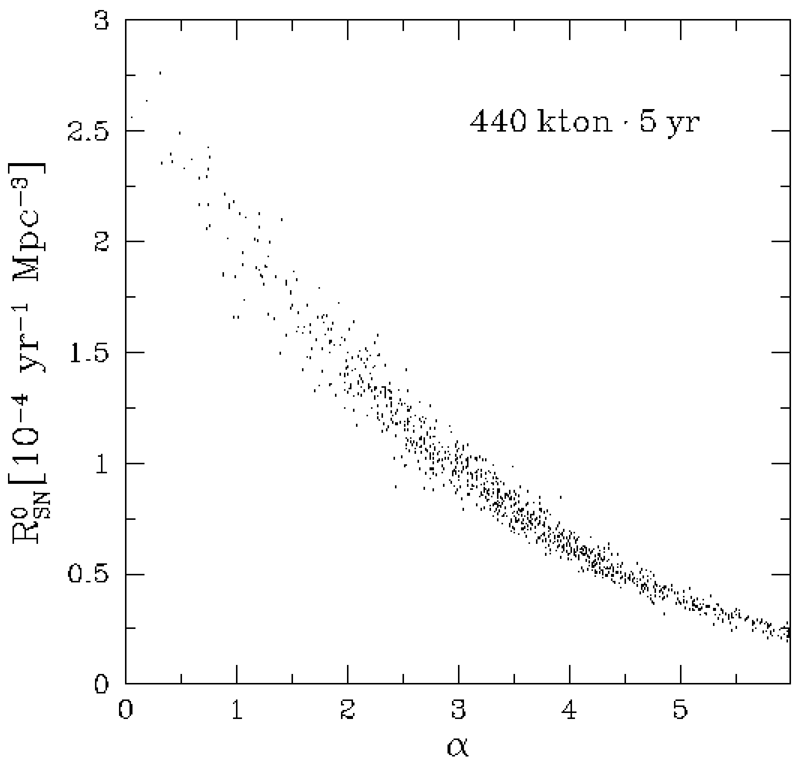
Comparison of model/obtained SN rate



- SRN observation well reproduces assumed SN rate history.

Model SN rate
22.5 kton 5 yr
440 kton 5 yr

Distribution of best fit parameters (2)



- Distribution of (α, $R_{SN}{}^0$) without parameter fixing.
- Even with Hyper-K or UNO, it is difficult to obtain the both values without prior knowledge.

$\alpha = 3.5 +/- 1.3$

$R_{SN}{}^0 = 0.88 +/- 0.48$

Part I

Supernova relic neutrinos and cosmic star formation history

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Conclusion of Part I

- SRN flux and event rate is investigated as an SFR indicator.
- In the calculation, three supernova neutrino spectrum, LL, TBP and KRJ, is adopted.
- In the near future, 10—30 MeV will be available as an energy window.
- SFR evolution at low-z could be inferred with accuracy of ~30% (8%) by using the detector of 22.5 kton 5 yr (440 kton 5 yr).

Brief overview

Supernova Relic Neutrinos

FINISHED!

- Diffuse backgr of past supern neutrino
- Flux estimate
- etector rmance
- Implications for cosmic star formation history

Supernova Neutrino Burst and Flavor Conversion

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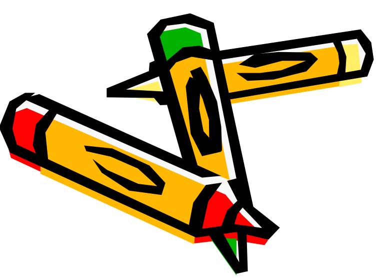
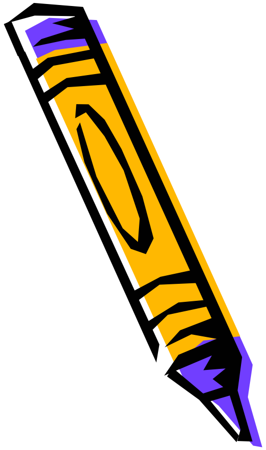
- Neutrino magnetic moment with normal/inverted mass hierarchy
- Expected signal at Super-K detector and its implications





Part II

Supernova neutrino oscillation with/without neutrino magnetic moment

1. Introduction
2. Formulation
3. Models for Numerical Calculation
4. Results & Discussion
5. Conclusions

Ando & Sato, Phys. Rev. D **67** (2003) 023004
Ando & Sato, Phys. Rev. D **68** (2003) 023003
Ando & Sato, JCAP **10** (2003) 001

Part II

Supernova neutrino oscillation with/without neutrino magnetic moment

1. **Introduction**
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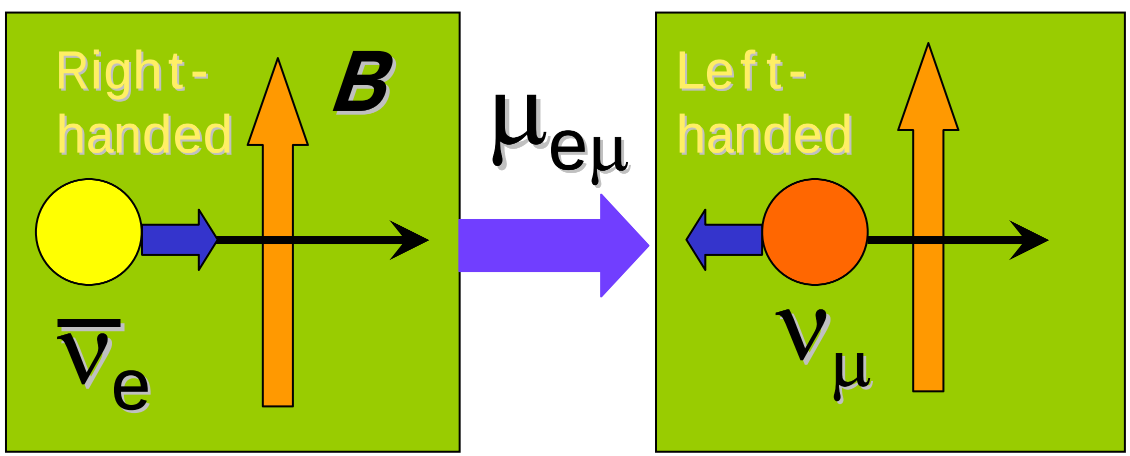
Neutrino magnetic moment

- We focus on the neutrino magnetic moment.
- If the neutrino has nonzero magnetic moment:
  1. Its helicity flips by the interaction with magnetic fields.
     - Conversion between neutrinos and antineutrinos.
  2. At the same time, its flavor can also be transformed. (spin-flavor precession)
  3. In matter, this can be resonantly caused, owing to potential difference among flavors. (Resonant spin-flavor (RSF) conversion)

Refs.

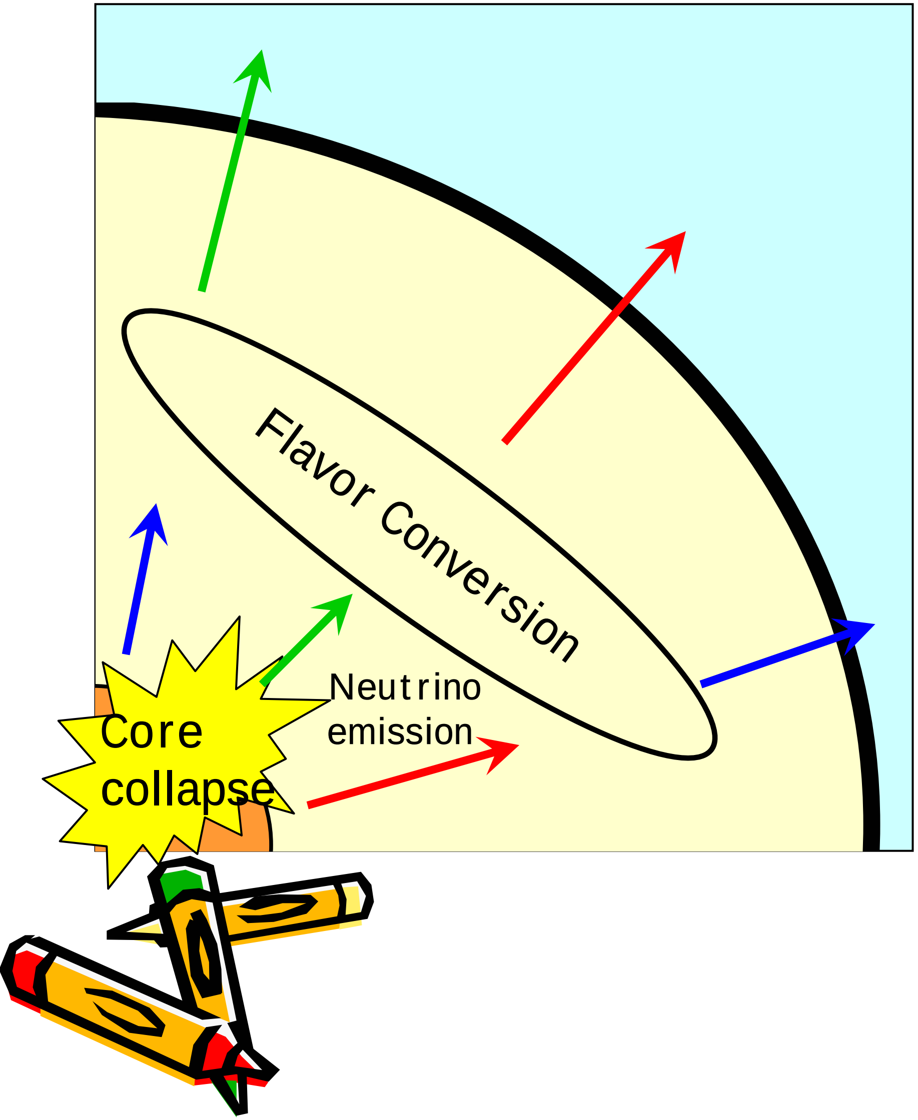
1. Cisneros 1970; Fujikawa & Shrock 1980
2. Schechter & Valle 1981
3. Lim & Marciano 1988; Akhmedov 1988



Why do we consider supernovae?

1. Very efficient neutrino emission
   - 99% of the gravitational binding energy is released as neutrinos.
   - All the three-flavor (e, μ, τ) neutrinos and antineutrinos are radiated.
2. The RSF effect can be very efficient
   - High density → Resonance condition is satisfied.
   - Strong magnetic field → Adiabatic resonance may be realized.

Flavor conversion (MSW or RSF) inside the supernova



- An observed neutrino spectrum are different from original one owing to flavor conversions.
- Flavor conversions inside the supernova are enhanced by both the MSW matter effect and the magnetic RSF effect.

Part II

Supernova neutrino oscillation with/without neutrino magnetic moment

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Two-component formulation

- For simplicity, we first discuss two-component.

$$i\frac{d}{dr}\begin{pmatrix}\bar{\nu}_e\\ \nu_\mu\end{pmatrix}=\begin{pmatrix}\sqrt{2}G_F n_B(1-2Y_e) & \mu_{e\mu}B\\ \mu_{e\mu}B & \frac{\Delta m_{12}^2}{2E_\nu}\cos 2\theta_{12}\end{pmatrix}\begin{pmatrix}\bar{\nu}_e\\ \nu_\mu\end{pmatrix}$$

Matter effect (potential difference between $\bar{\nu}_e$ and ν_μ).

A parameter which determines whether the resonance is adiabatic or not.

- Two diagonal components have the same value at resonance point.
- At resonance, if nondiagonal element $\mu_{e\mu}\boldsymbol{B}$ is sufficiently large, a complete conversion is realized (adiabatic resonance).

Comparison of MSW and RSF

RSF conversion
(between $\bar{\nu}_e$ and $\nu_{\mu,\tau}$)

$$\frac{\Delta m^2}{E_\nu} \simeq G_F n_B \underline{(1-2Y_e)}$$

MSW conversion
(between ν_e and $\nu_{\mu,\tau}$)

$$\frac{\Delta m^2}{E_\nu} \simeq G_F n_B \underline{Y_e}$$

- Because $Y_e \sim 0.5$ ($1-2Y_e \sim 0$) in the supernova envelope, RSF occurs in deeper region than MSW.
- Each conversion (MSW and RSF) occurs twice at different density regions (MSW-L,H; RSF-L,H), corresponding to two values of Δm^2 (Δm_{12}^2, Δm_{13}^2).

Resonance and mass hierarchy

- In RSF-H and MSW-H, conversion channel is very sensitive to the neutrino mass hierarchy.

Resonance	Normal hierarchy	Inverted hierarchy
RSF-H	$\bar{\nu}_e \leftrightarrow \nu'_\tau$	$\nu_e \leftrightarrow \bar{\nu}'_\tau$
RSF-L	$\bar{\nu}_e \leftrightarrow \nu'_\mu$	$\bar{\nu}_e \leftrightarrow \nu'_\mu$
MSW-H	$\nu_e \leftrightarrow \nu'_\tau$	$\bar{\nu}_e \leftrightarrow \bar{\nu}'_\tau$
MSW-L	$\nu_e \leftrightarrow \nu'_\mu$	$\nu_e \leftrightarrow \nu'_\mu$

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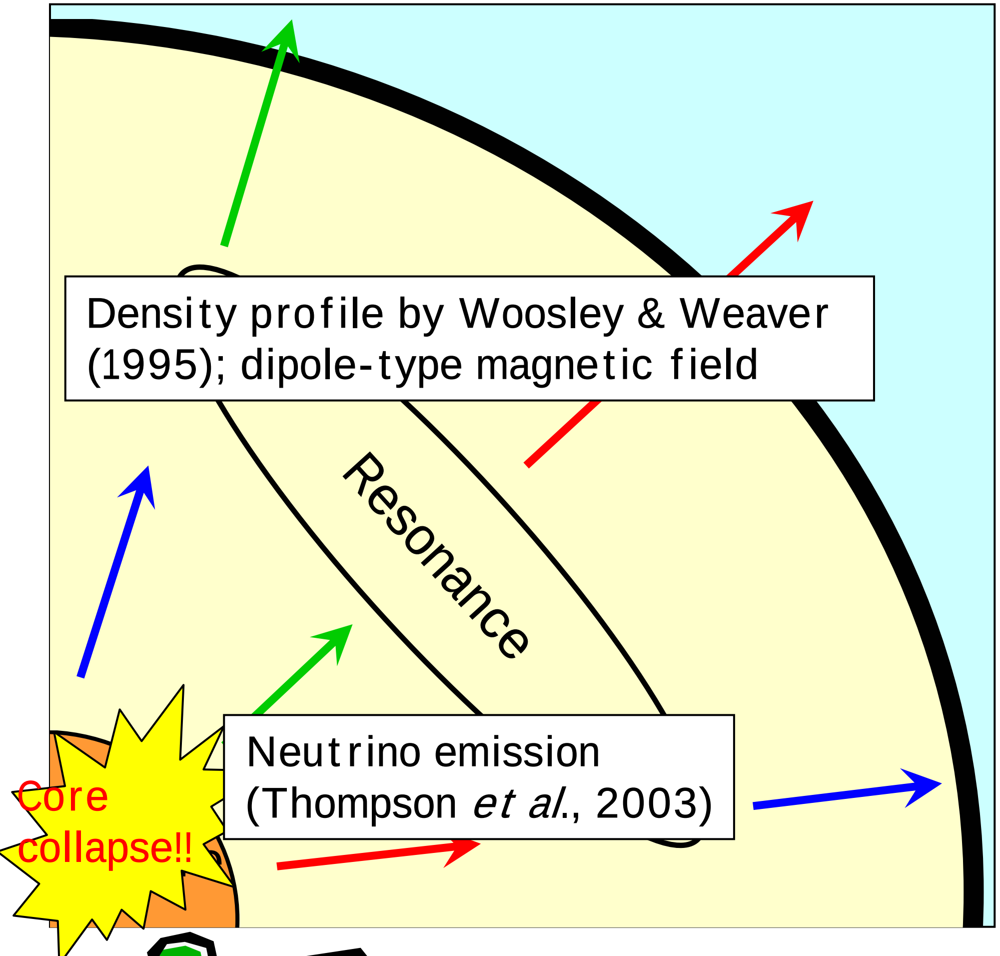
5. Conclusions

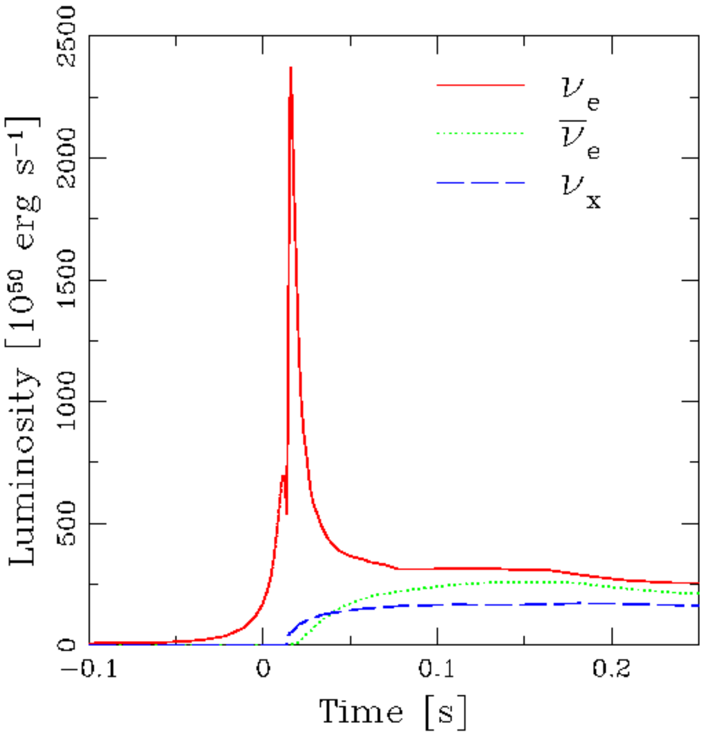
Models for supernova properties



1. Original neutrino spectrum: Models by Thompson, Burrows & Pinto (2003)
2. Density profile: 15M$_3$ progenitor model by Woosley & Weaver (1995)
3. Magnetic field structure: Dipole structure; strength is normalized at the surface of iron core (B_0).

cf. Observation of the surface magnetic field of white dwarfs gives value 10^7—10^9 G. We take to 10^{10} G considering the possible decay.

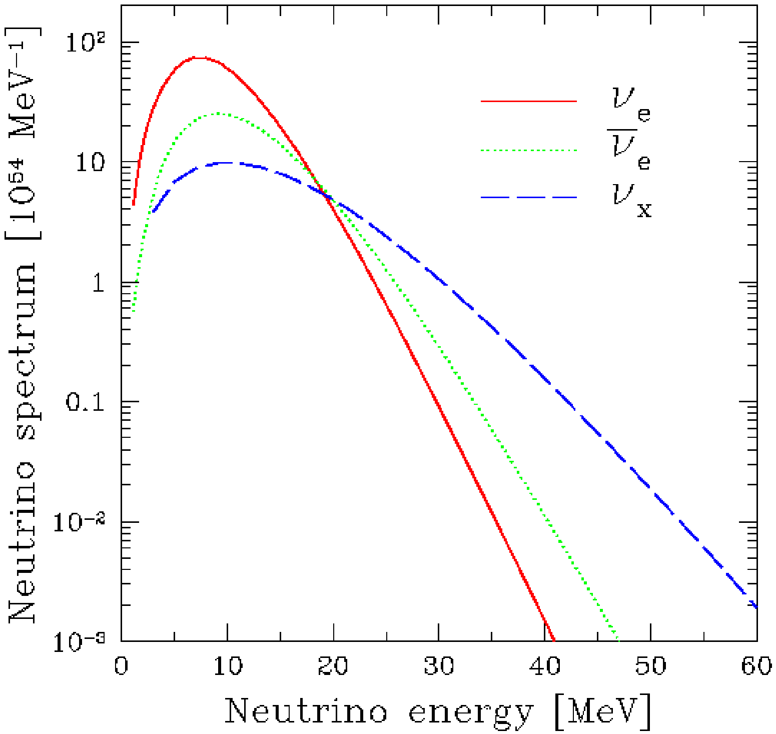
Original neutrino signal



15M$_3$ model by Thompson et al. (2003)

- Their calculation ends around 0.25 s after core bounce.
  - The shock effect can be neglected.
- There exists a sharp peak of ν_e. (neutronization burst)

Original neutrino signal



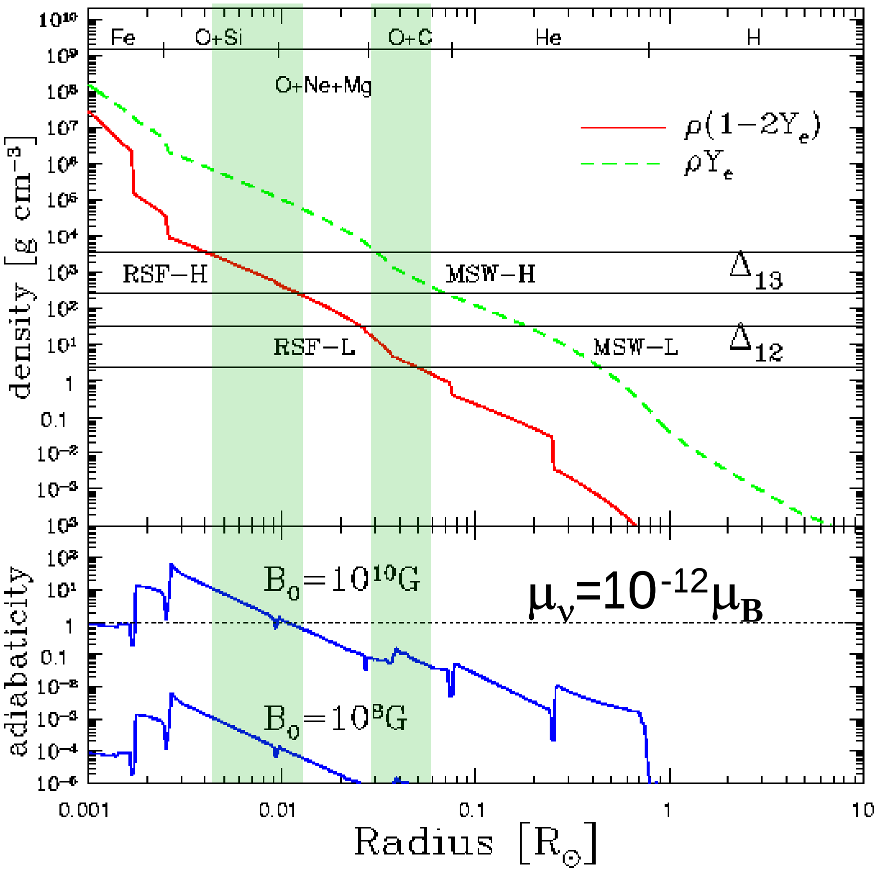
15M$_3$ model by Thompson et al. (2003)

- Their calculation ends around 0.25 s after core bounce.
  - The shock effect can be neglected.
- There exists a sharp peak of ν_e. (neutronization burst)
- Hierarchy of the average energy:

$$\langle E^0_{\nu_e} \rangle < \langle E^0_{\bar{\nu}_e} \rangle < \langle E^0_{\nu_x} \rangle$$

- Flavor conversion changes this relation.

Supernova progenitor model



- $15M_3$ progenitor model by Woosley & Weaver (1995).
- RSF-H occurs at O+Si; RSF-L and MSW-H at O+C; and MSW-L at He layers.
- RSF-H becomes adiabatic when the magnetic field is sufficiently strong, on the other hand, RSF-L is always nonadiabatic.

Neutrino parameters

Model	B_0 [G]	Mass hierarchy	$\sin^2 2\theta_{13}$	Group
MSW-NOR-S	0	Normal	10^{-6}	A
MSW-NOR-L	0	Normal	0.04	A
MSW-INV-S	0	Inverted	10^{-6}	A
MSW-INV-L	0	Inverted	0.04	B
RSF-NOR-S	10^{10}	Normal	10^{-6}	B
RSF-NOR-L	10^{10}	Normal	0.04	B
RSF-INV-S	10^{10}	Inverted	10^{-6}	A
RSF-INV-L	10^{10}	Inverted	0.04	C

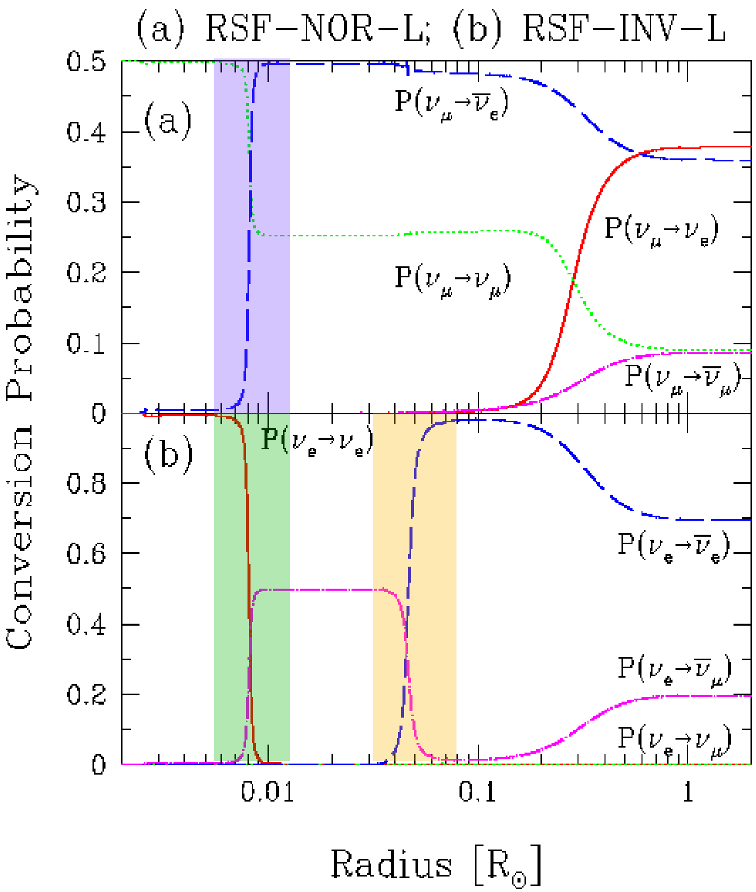
- In this study, $\mu_\nu = 10^{-12}\ \mu_B$ is assumed.
- Each model is further categorized into three groups A, B and C, according to the detected $\bar{\nu}_e$ signal.

Part II

Supernova neutrino oscillation with/without neutrino magnetic moment

1. Introduction
2. Formulation
3. Models for Numerical Calculation
4. **Results & Discussion**
5. Conclusions

Conversion probability (large θ_{13})



- Relevant conversion

RSF-NOR-L:

$$\nu_{\mu,\tau} \longrightarrow \bar{\nu}_e$$

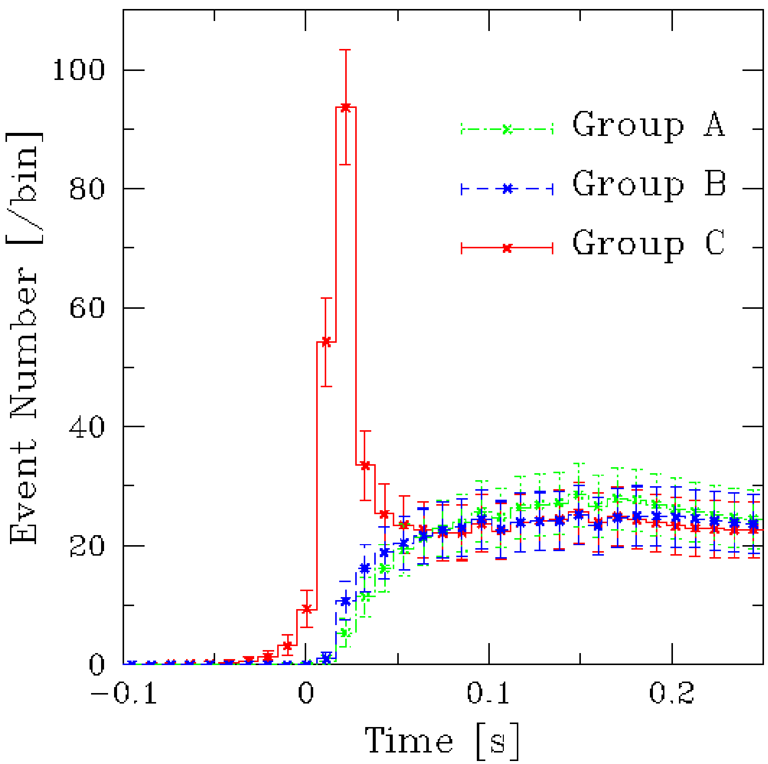
RSF-H

RSF-INV-L:

$$\nu_e \longrightarrow \bar{\nu}_{\mu,\tau} \longrightarrow \bar{\nu}_e$$

RSF-H MSW-H

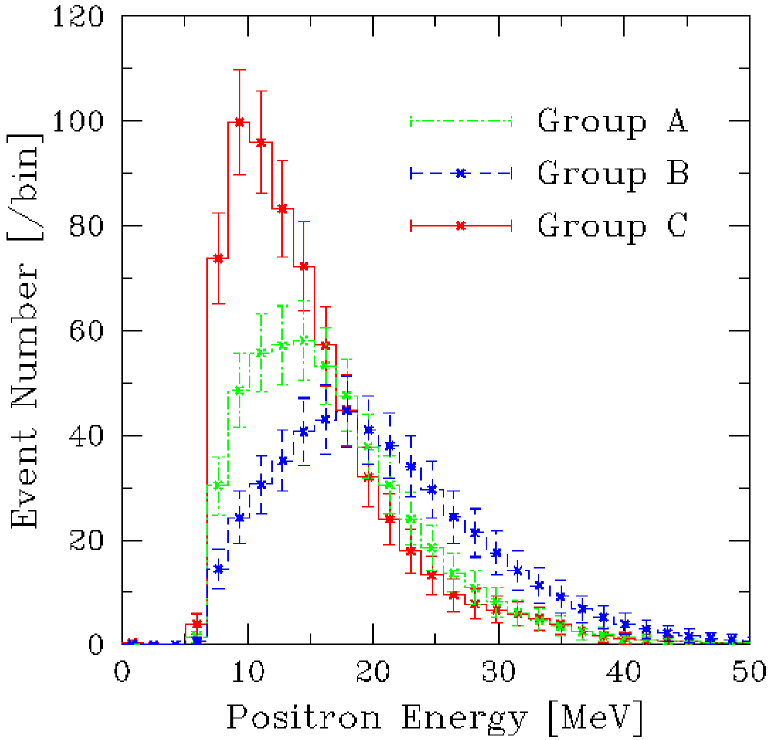
Time profile at SK



D = 10 kpc

- Because $\bar{\nu}_e$ p → e^+ n is dominant process, the observed signal is almost that of $\bar{\nu}_e$.
- Group C indicates strong peak of neutronization burst, because the original ν_e are converted.
- Other two groups are almost degenerate.

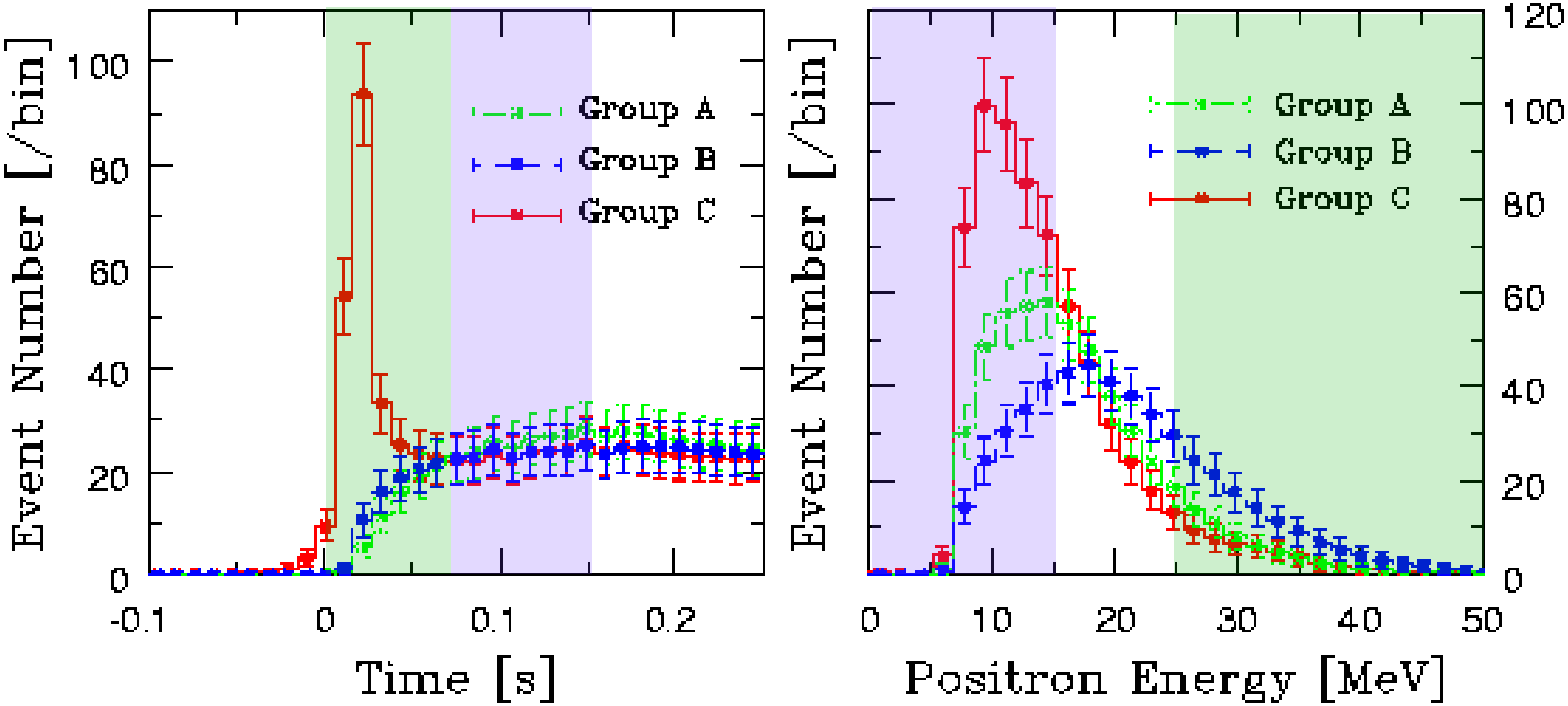
Number spectrum at SK



D = 10 kpc

- From the spectrum at SK, the degeneracy between group A and B will be solved.
- Group C indicates the softest spectrum as well as a characteristic time profile.

Simple indicators of the RSF effect

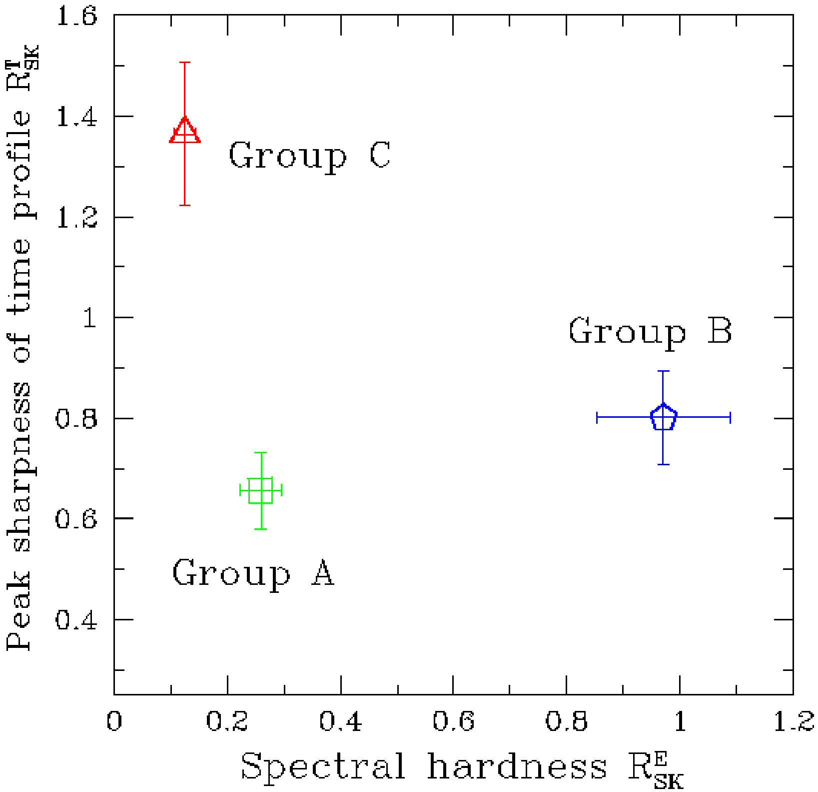


$$R_{\mathrm{SK}}^{\mathrm{E}} = \frac{\text{Number of events for } E_e > 25 \text{ MeV}}{\text{Number of events for } E_e < 15 \text{ MeV}},$$

$$R_{\mathrm{SK}}^{\mathrm{T}} = \frac{\text{Number of events for } 0 < t/\text{ms} < 75}{\text{Number of events for } 75 < t/\text{ms} < 150}$$

- We use these two quantities as simple indicators of the RSF effect.

R^E vs R^T plot at SK



- Error bars include only statistical errors, and are at 1σ level.
- Each group is well separated from one another on this plane.
- We cannot solve the degeneracy within each group.
- The signal of ν_e may be a good probe for that.

Neutrino parameters

Model	B_0 [G]	Mass hierarchy	$\sin^2 2\theta_{13}$	Group
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MSW-NOR-L	0	Normal	0.04	A
MSW-INV-S	0	Inverted	10^{-6}	A
MSW-INV-L	0	Inverted	0.04	B
RSF-NOR-S	10^{10}	Normal	10^{-6}	B
RSF-NOR-L	10^{10}	Normal	0.04	B
RSF-INV-S	10^{10}	Inverted	10^{-6}	A
RSF-INV-L	10^{10}	Inverted	0.04	C

- In this study, $\mu_\nu = 10^{-12}\ \mu_B$ is assumed.
- Each model is further categorized into three groups A, B and C, according to the detected $\bar{\nu}_e$ signal.

Part II

Supernova neutrino oscillation with/without neutrino magnetic moment

1. Introduction
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Conclusion of Part II

- We investigated the RSF effect of supernova neutrinos for both normal and inverted mass hierarchy.
- If the RSF effect occurs efficiently, the detected signal is expected to be strongly dependent on the mass hierarchy.
- In particular for the RSF-INV-L model, there will be a sharp peak of neutronization burst in the events detected at SK.
- The neutrino spectra would be also different between the neutrino models.

Brief overview

Supernova Relic Neutrinos

- Diffuse backgr… of past supern… neutrino…
- Flux … estimate
- … etector … rmance
- Implications for cosmic star formation history

FINISHED!

Supernova Neutrino Burst and Flavor Conversion

- Flavor conversi… ide supernova e…
- Neutrin… ic mome… no… erted mass … ly
- E… cted signal at Super-K detector and its implications

FINISHED!