9 April 2019

Prospects of Neutrino Physics @IPMU

# Tomography by neutrino pair beam

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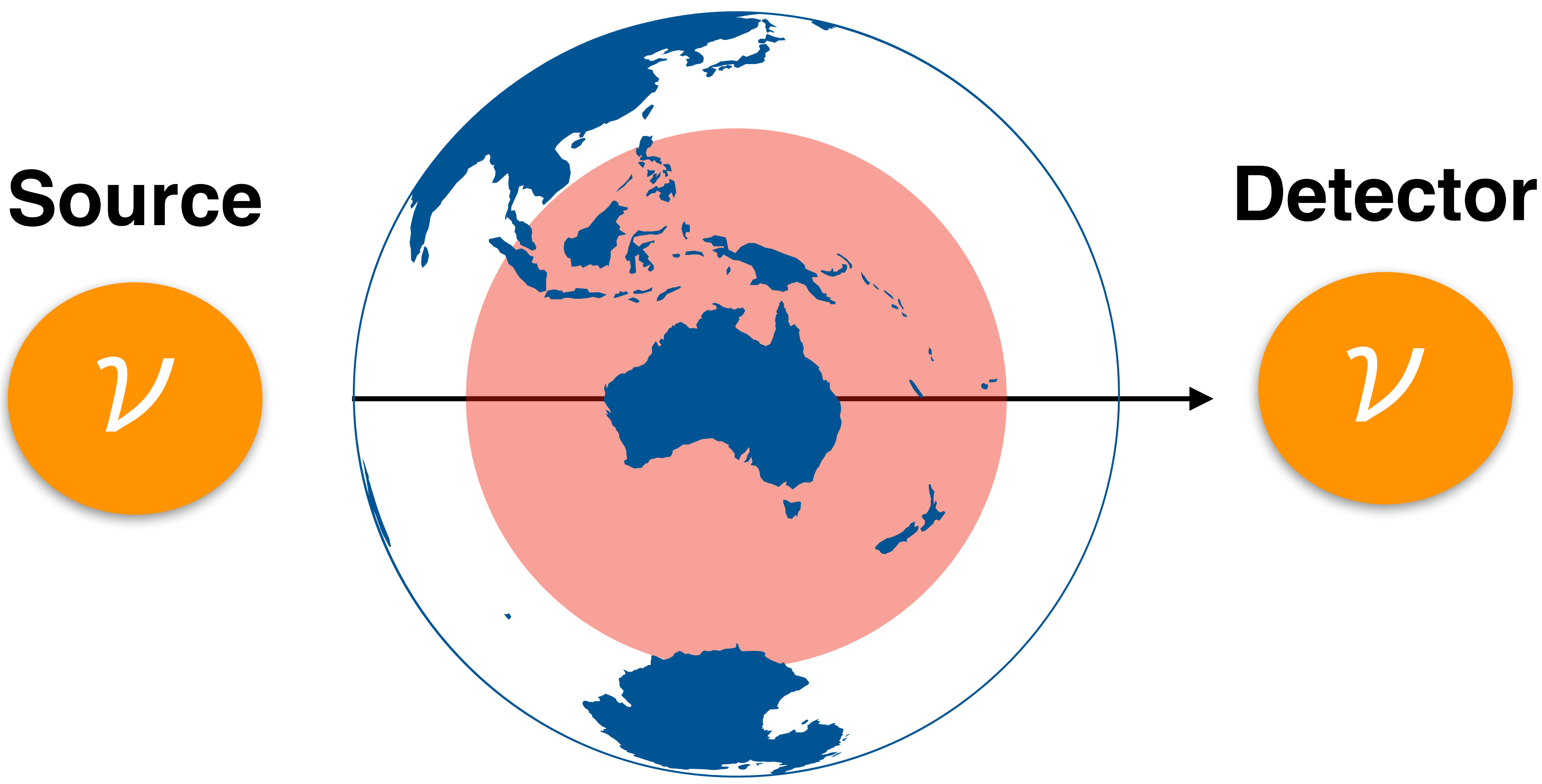
Phys.Lett.B785(2018) 536-542 [arXiv:1805.10793]

NIIGATA UNIVERSITY

# Neutrino Tomography

- Thanks to the remarkable effort, our understanding of neutrino has improved greatly.
- Neutrino Tomography is one of the application of the Neutrino Physics.




**Imaging of the Earth's interior structure by using neutrino**

# Neutrino Tomography

**Mainly we have two method for neutrino tomography.**

## Neutrino Absorption Tomography

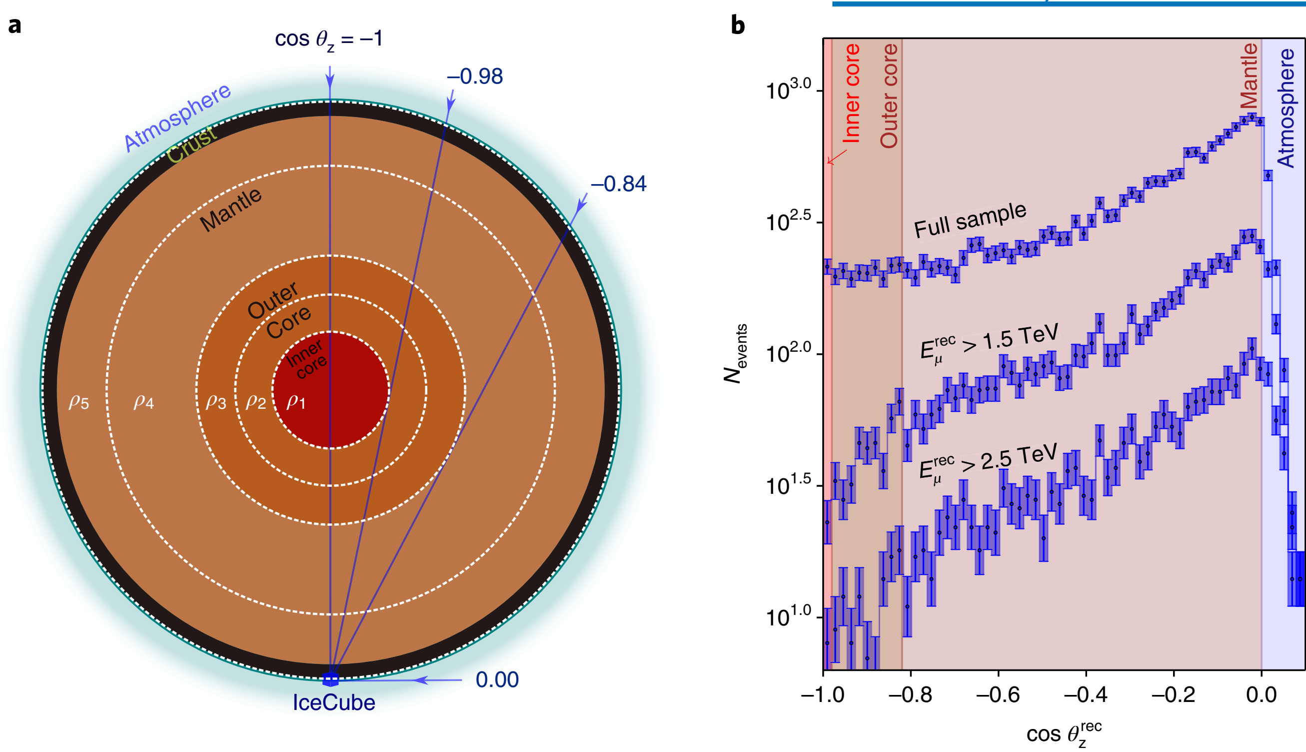
- **The image of the object can be reconstructed by measuring the absorption rates of high energy neutrino passing through the different angles.**
- **This is similar to X-ray computed tomography(X-ray CT).**

## Neutrino Oscillation Tomography

- **This aim to reconstruct the density profile by matter effect of the neutrino oscillation.**

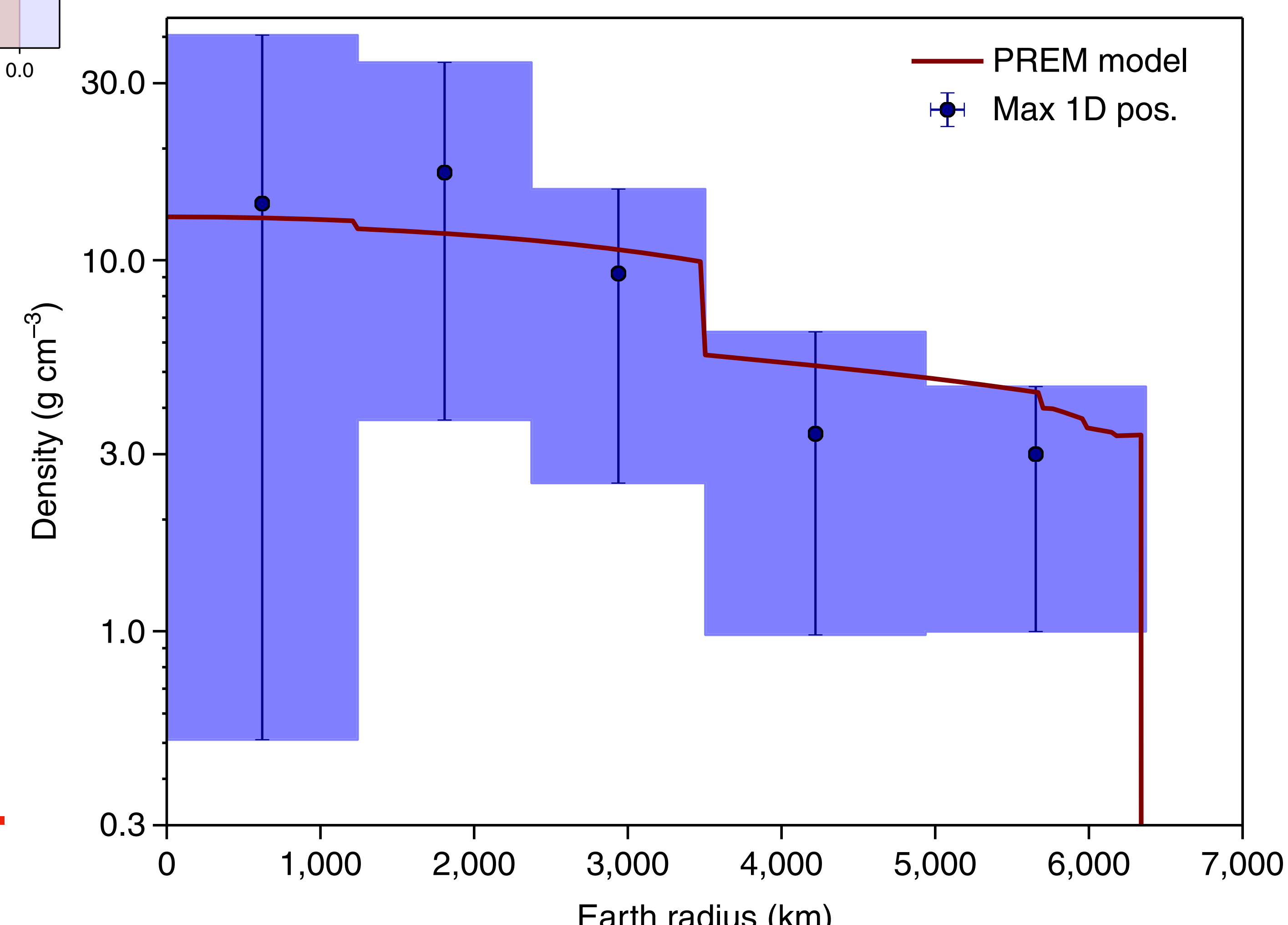
# Neutrino Absorption Tomography

[A.Donini, S.Palomares-Ruiz, J.Salvado, Nature Phys. 15 (2019) no.1, 37-40]




**They used the one-year of muon atmospheric neutrino data with energies extending above the TeV scale collected by the IceCube telescope.**

**20,145 muons was detected / 343.7 days**




**Non-gravitational measurement of Earth's mass**

$$M_\oplus^\nu = (6.0^{+1.6}_{-1.3}) \times 10^{24}\mathrm{kg}$$

$$M_\oplus^{grav} = (5.9722 \pm 0.0006) \times 10^{24}\mathrm{kg}$$

**It requires more statistics for feasibility of the neutrino tomography.**

# Neutrino Oscillation Tomography

## Evolution equation in matter

$$i\frac{d}{dx}\begin{pmatrix} A_{\nu_e\to\nu_e} \\ A_{\nu_e\to\nu_\mu}\end{pmatrix} = \left[U\begin{pmatrix} 0 & 0 \\ 0 & \frac{\Delta m^2}{2E}\end{pmatrix}U^\dagger + \begin{pmatrix} V_{CC}(x) & 0 \\ 0 & 0\end{pmatrix}\right]\begin{pmatrix} A_{\nu_e\to\nu_e} \\ A_{\nu_e\to\nu_\mu}\end{pmatrix}$$

**Effective potential is written as**

$$V_{CC}(x) = \sqrt{2}G_F n_e(x)$$

**The electron number density is translated into the matter density.**

$$n_e(x) \simeq \frac{\rho(x)}{2m_p}$$

$$\begin{aligned} \rho &= m_p n_p + m_n n_n + m_e n_e \\ &\simeq m_N(n_p + n_n) \\ &\simeq m_N 2n_e \\ \therefore n_e &\simeq \frac{\rho}{2m_N} \end{aligned}$$

$$m_p \simeq m_n \gg m_e$$

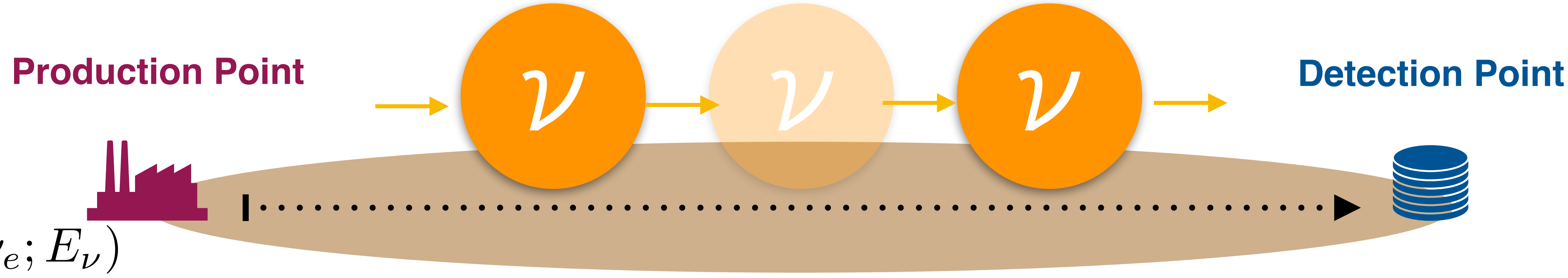
$$n_e = n_p = n_n$$

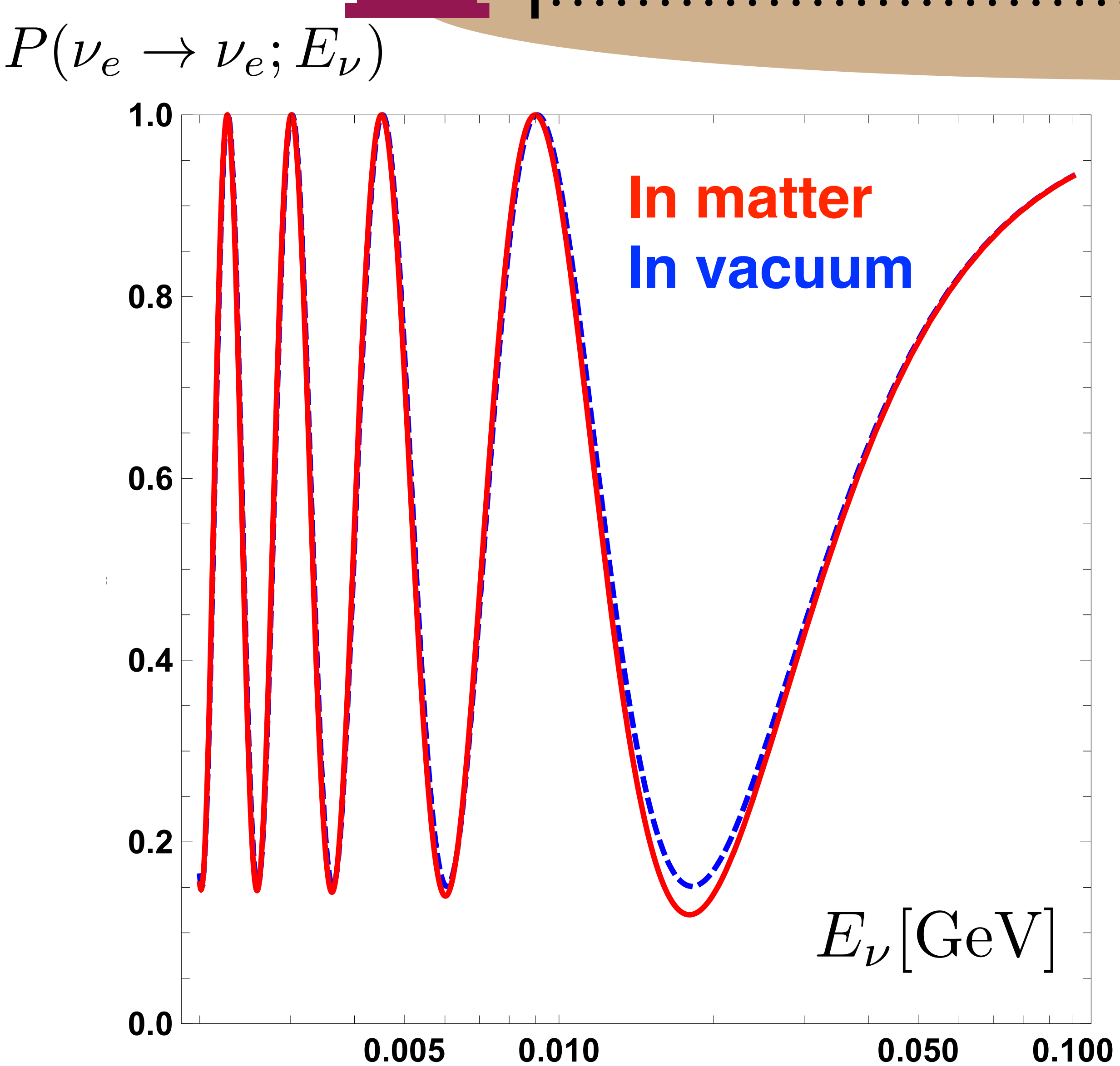
**Probability is calculated as follow**

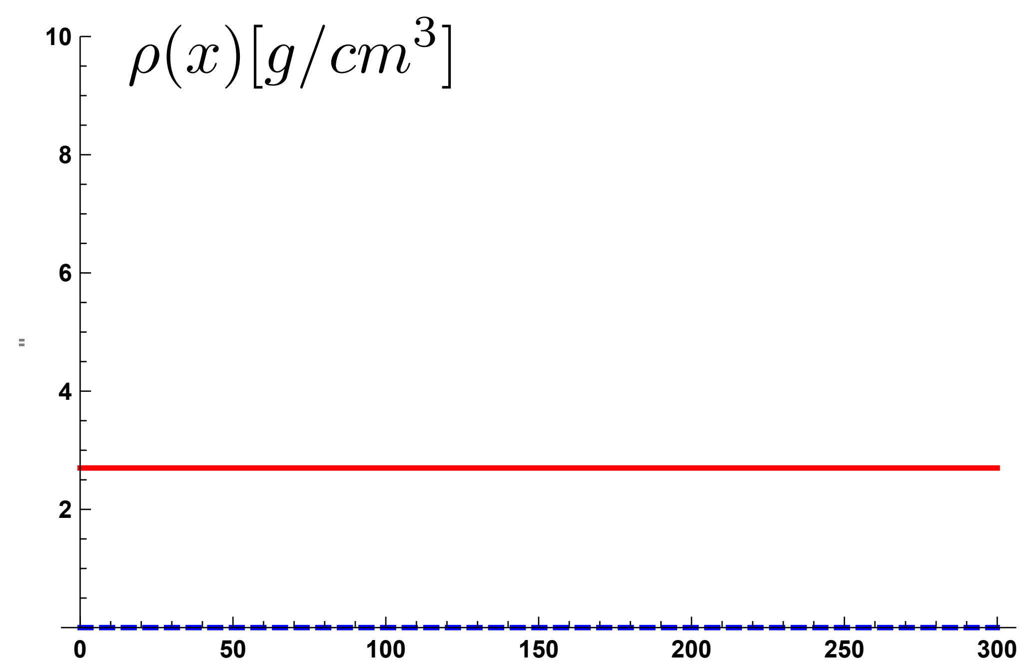
$$P_{\nu_\alpha\to\nu_\beta}(E_\nu, x) = |A_{\nu_\alpha\to\nu_\beta}(E_\nu, x)|^2$$

# Neutrino Oscillation Tomography

- **The energy spectrum of the neutrino oscillation probability is distorted, compared to the vacuum one, by the interaction with matter through which neutrinos pass from the production to the detection point.**



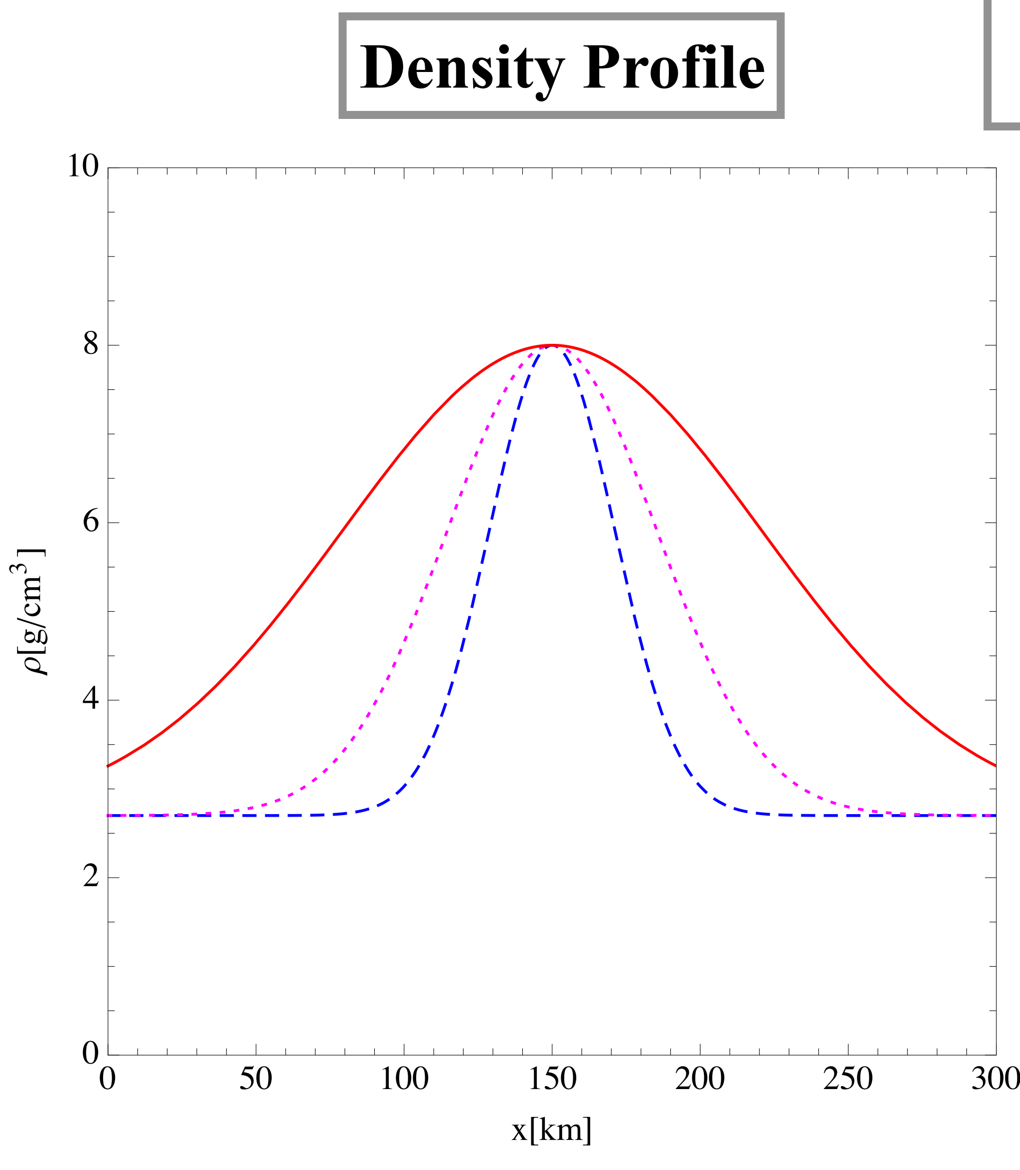



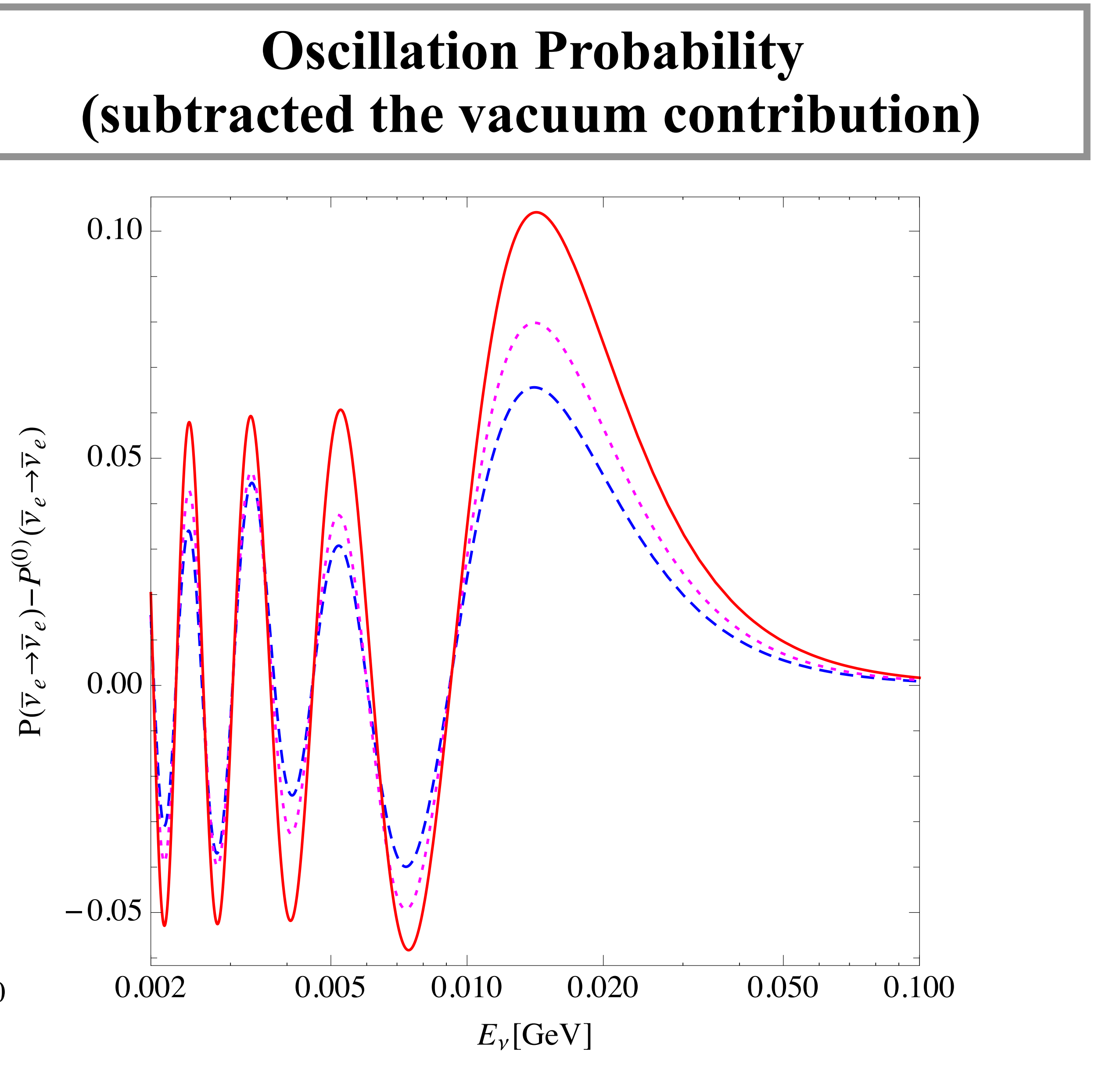




$$x = 300\ [km]$$
$$\Delta m^2 = 7.5 \times 10^{-5}\ [eV^2]$$
$$\theta = \frac{33.56}{180}\pi$$

# Neutrino Oscillation Tomography

- Energy spectrum of the oscillation probability
  changes according to the density profile.




- But this effect is small.
- So It requires the precise measurement of the energy spectrum.

# Neutrino Oscillation Tomography

## There are many approaches.

### Neutrino Source

Atmospheric

W.Winter;
C.Rott, A.Taketa, D. Bose; …

Solar

E.K.Akhmedov, M.Tortola, J.Valle;
A.N.Ioannisiam, A.Yu.Smirnov

Supernova

E.K.Akhmedov, M.Tortola, J.Valle;
M.Lindner, T.Ohlsson, R.Tortola, W.Winter

man-made beam

V.Ermilova, V.Tsarev, V.Chechin;
T.Ohlsson, W.Winter, …

### Analysis

$\chi 2$ analysis

Likelihood analysis

Several papers

Fourier analysis

E.K.Akhmedov, M.Tortola, J.Valle;
T.Ota, J.Sato; ….

Expansion analysis

A.N.Ioannisiam, A.Yu.Smirnov;…

### Target

Density profile of entire Earth

Density fluctuation

Earth's core

Z/A ratio

Specific site

# Neutrino Oscillation Tomography

## Open Questions

- How do we realize accurate energy spectrum measurement ?
- How do we reconstruct the Earth's density distribution ?

# Neutrino Oscillation Tomography

## Open Questions

**Our Approach**

- How do we realize accurate energy spectrum measurement ?
  → Powerful source (Neutrino pair beam)
- How do we reconstruct the Earth's density distribution ?
  → Reconstruction method with 2nd order perturbation

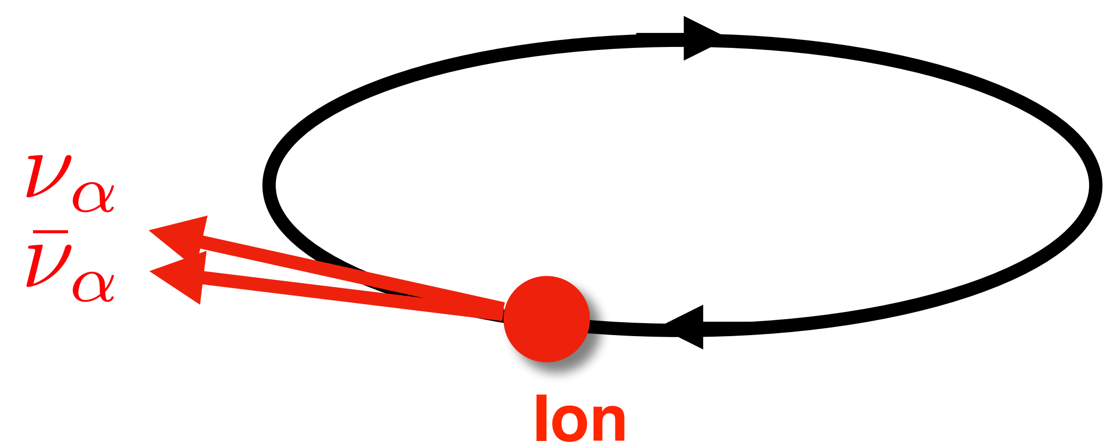
# Neutrino Pair Beam

- The pair beam, which has been proposed recently, can produced a large amount of neutrino pairs from the circulating partially stripped ions.

[Yoshimura, Sasao, Phys. Rev. D 92, 073015 (2015)]

**Characteristics of the Neutrino Pair Beam**

- It generates the all flavor neutrino pairs
  $(\nu_e, \overline{\nu_e}), (\nu_\mu, \overline{\nu_\mu}), (\nu_\tau, \overline{\nu_\tau})$
- Very high intensity flux of neutrino beam
- High beam directivity
- Mainly electron neutrino pair being generated




- Neutrino tomography requires the precise measurement of the energy spectrum for the precise reconstruction of the density profile.
- High event rate (high flux) is essential.

# Neutrino Pair Beam

| Source | Energy | Flux |
|---|---|---|
| Atmospheric : $\nu_\mu$ $(\cos\theta_Z = 0)$ | 3.2 GeV | $3.6 \times 10^2 [\mathrm{m}^{-2}\mathrm{s}^{-1}]$ |
| Solar | 10MeV | $10^4 [\mathrm{m}^{-2}\mathrm{s}^{-1}]$ |
| T2K at SK : $\nu_\mu$ | 1GeV | $2 \times 10^4 [\mathrm{m}^{-2}\mathrm{s}^{-1}]$ |
| Beta beam at 100 km : $\bar{\nu}_e$ | 581 MeV (average) | $2.1 \times 10^5 [\mathrm{m}^{-2}\mathrm{s}^{-1}]$ |
| Neutrino Pair Beam at 100 km | 100 MeV | $\sim 10^{10}$ $[\mathrm{m}^{-2}\mathrm{s}^{-1}]$ |
| Neutrino Pair Beam at 300 km | 100 MeV | $\sim 10^{9}$ $[\mathrm{m}^{-2}\mathrm{s}^{-1}]$ |

Atmospheric : M. Honda et.al., PhysRevD.92.023004

Solar : J. N. Bahcall et.al., New J. Phys. 6 (2004) 63

T2K : K. Abe et al. Phys. Rev. D 87 (2013) no.1, 012001

Beta beam : P. Zucchelli, Phys. Lett. B 532 (2002) 166

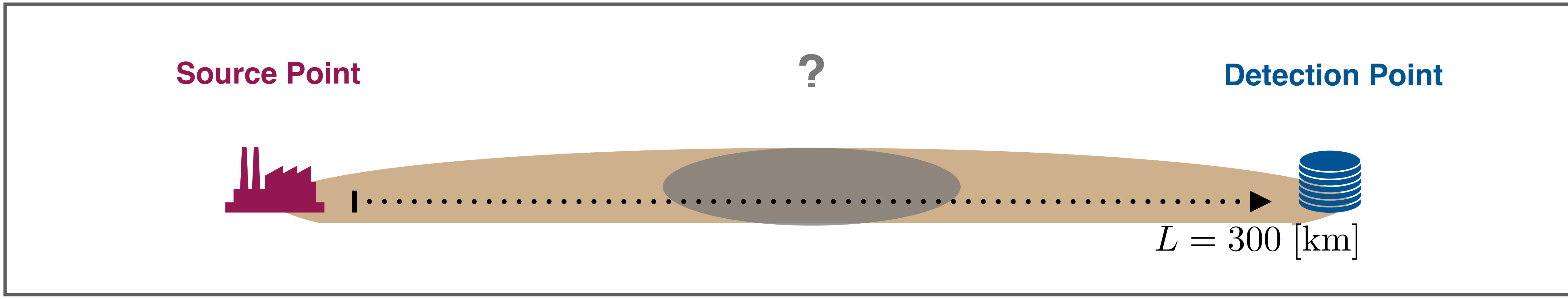
Neutrino Pair Beam : M.Yoshimura, N.Sasao, Phys.Rev.D92(2015) no.7, 073015

**Production amount of neutrino (estimation)**

nuMAX (Neutrino Factory) : $\sim 10^{20}$ / yr

NPB : $\sim 10^{22}$ / yr

# Toy Model




- **We consider the symmetric density profile.**

**e.g.**

$$\rho(x) = \bar{\rho} + (\rho_l - \bar{\rho}) \exp\left[-\frac{\left(x-\frac{L}{2}\right)^2}{D_l^2}\right]$$

**L : length of the baseline**
**$D_l$ : width of the lump**

- **We consider the low energy $\bar{\nu}_e \longrightarrow \bar{\nu}_e$ oscillation.**

$$E_\nu : 2 \sim 100 \text{ [MeV]}$$

**The neutrino energy threshold ≃1.806 MeV.**

- **We assume the huge liquid Argon as the neutrino detector.**

**Fiducial volume $10^5$ m$^3$**

**e.g. HK's volume $2.6 \times 10^5$ m$^3$**

http://www.hyper-k.org/overview.html

**We don't discuss about systematic error.**

# Statistical Analysis

**We estimate how precisely the width ( $D_*$ ) and density( $\rho_*$ ) of the lump can be reconstructed under this set-up.**

$$\rho(x) = \bar{\rho} + (\rho_l - \bar{\rho}) \exp\left[ -\frac{(x - \frac{L}{2})^2}{D_l^2} \right] \qquad \bar{\rho} = 2.7[\mathrm{g/cm^3}]$$

**We perform the $\chi^2$ analysis.**

$$\Delta\chi^2 = \sum_{i=1}^{N_b} \frac{\left[ N(E_i)|_{D_*,\rho_*} - N(E_i)|_{D_l,\rho_l} \right]^2}{\sigma^2(E_i)}$$

**$N_b = 100$ : the number of energy bin**

**N (Event number) = flux × oscillation probability × detection rate**

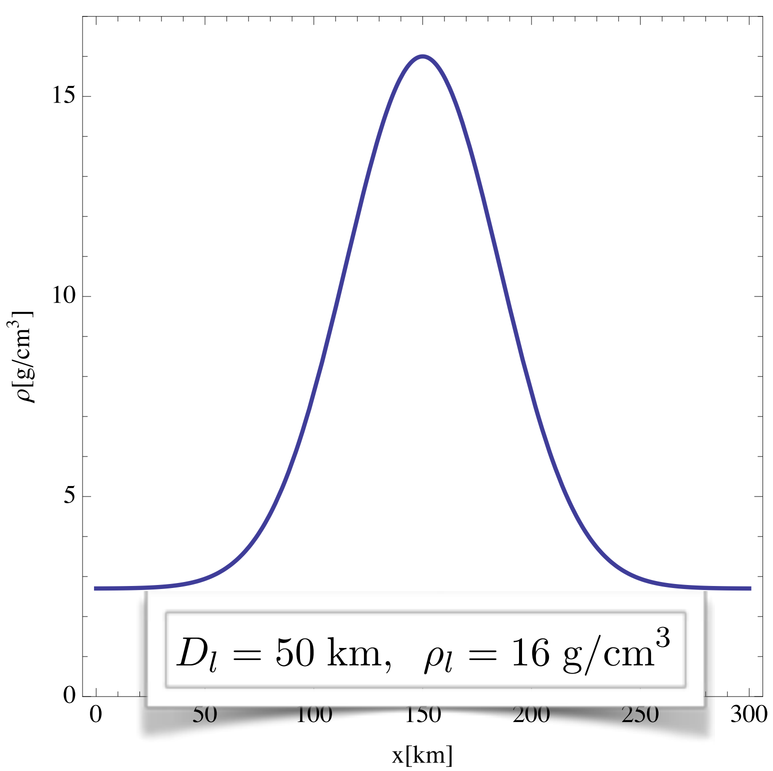
**We assume 1 year as experimental running time.**

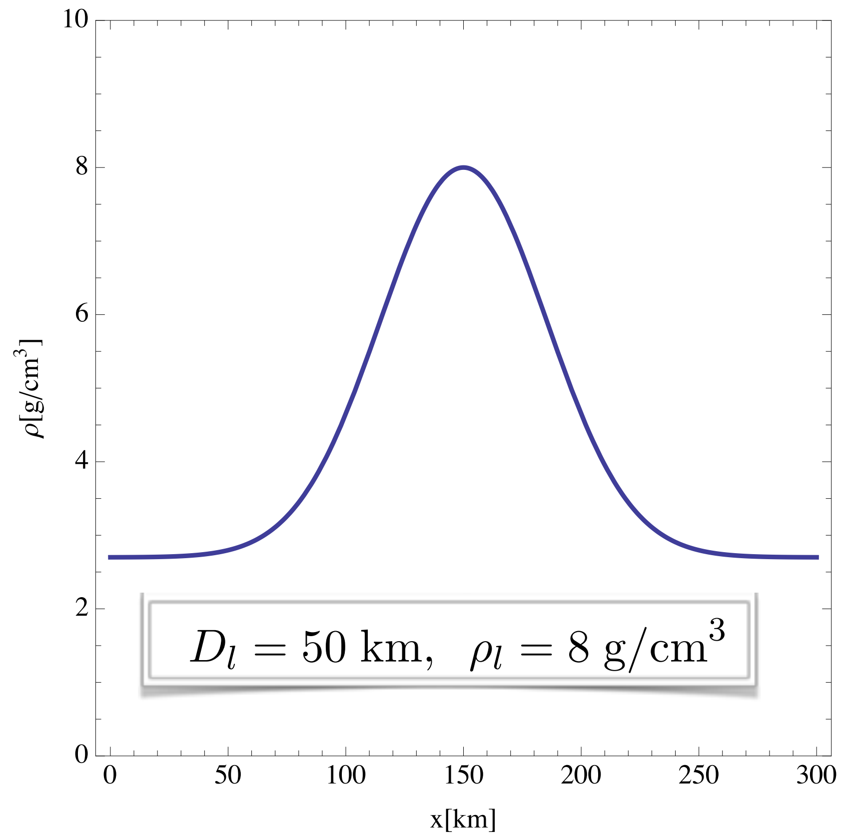
- **We only consider the statistical error in this calculation.**
- **(It is not included the systematic error)**

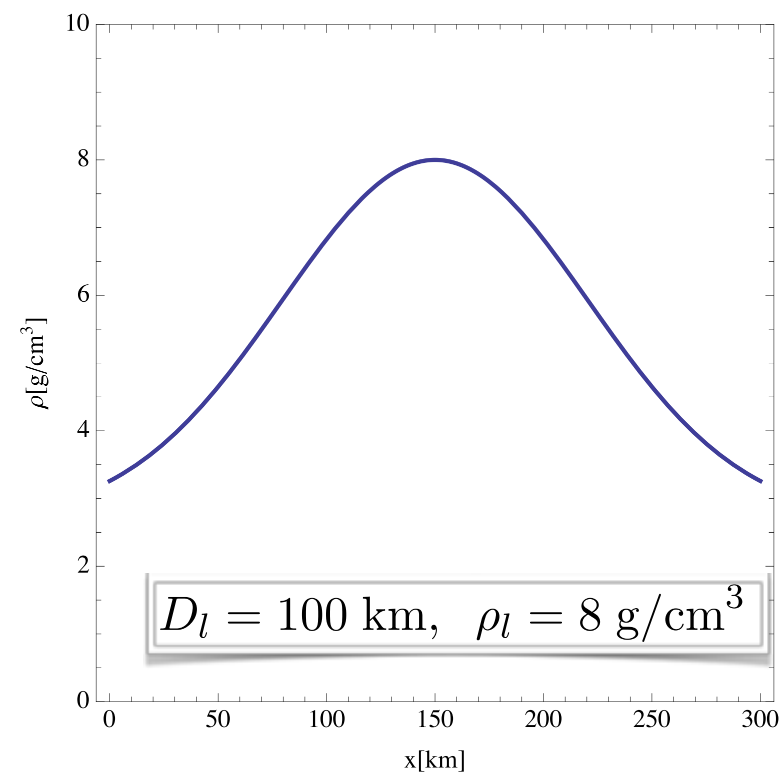
# Statistical Analysis

**We assume the 3 density profiles.**

$$\rho(x) = \bar{\rho} + (\rho_l - \bar{\rho}) \exp\left[ -\frac{\left(x - \frac{L}{2}\right)^2}{D_l^2} \right]$$

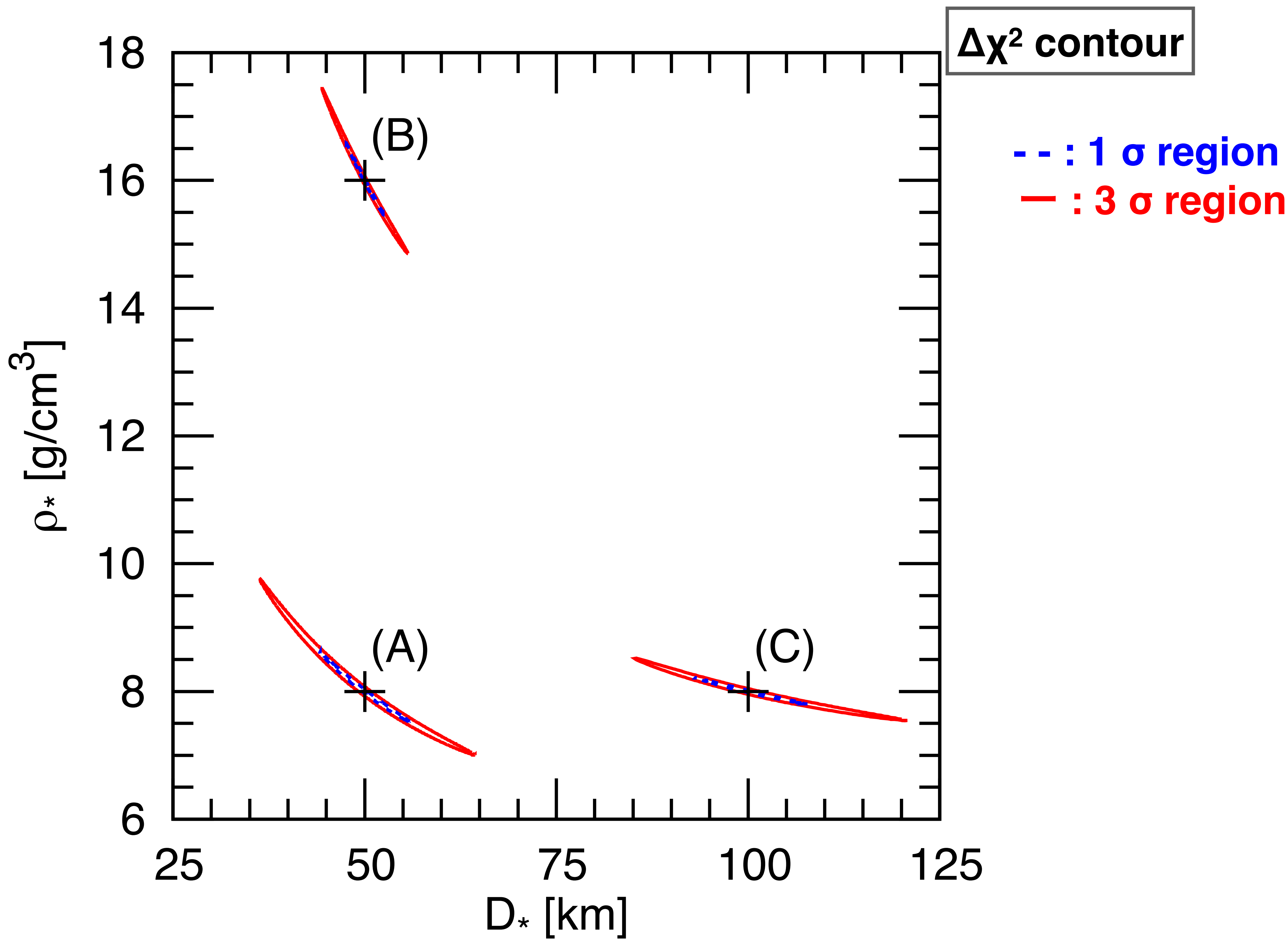


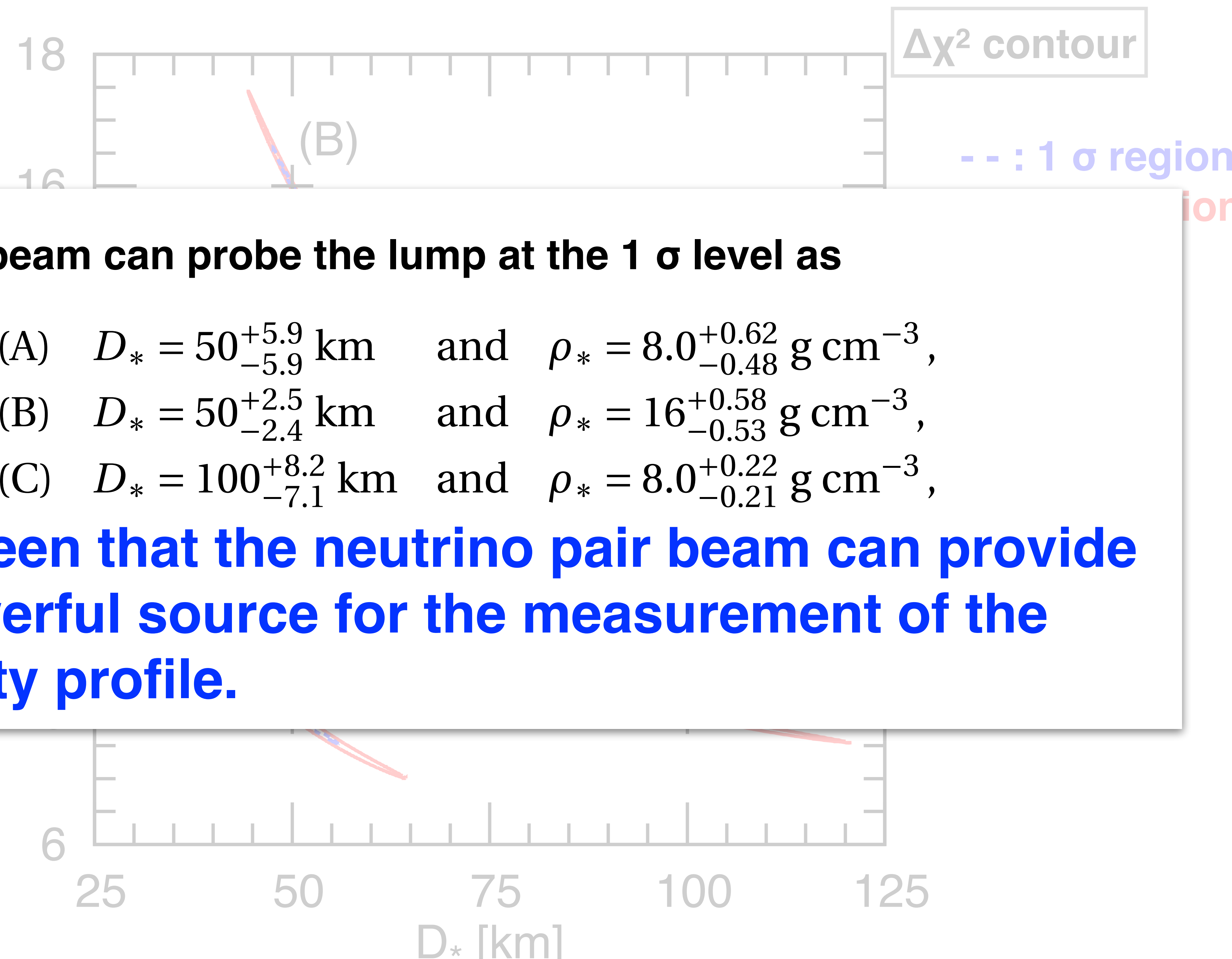
# Results

**We assume the 3 density profiles.**



# Results

We assume the 3 density profiles.

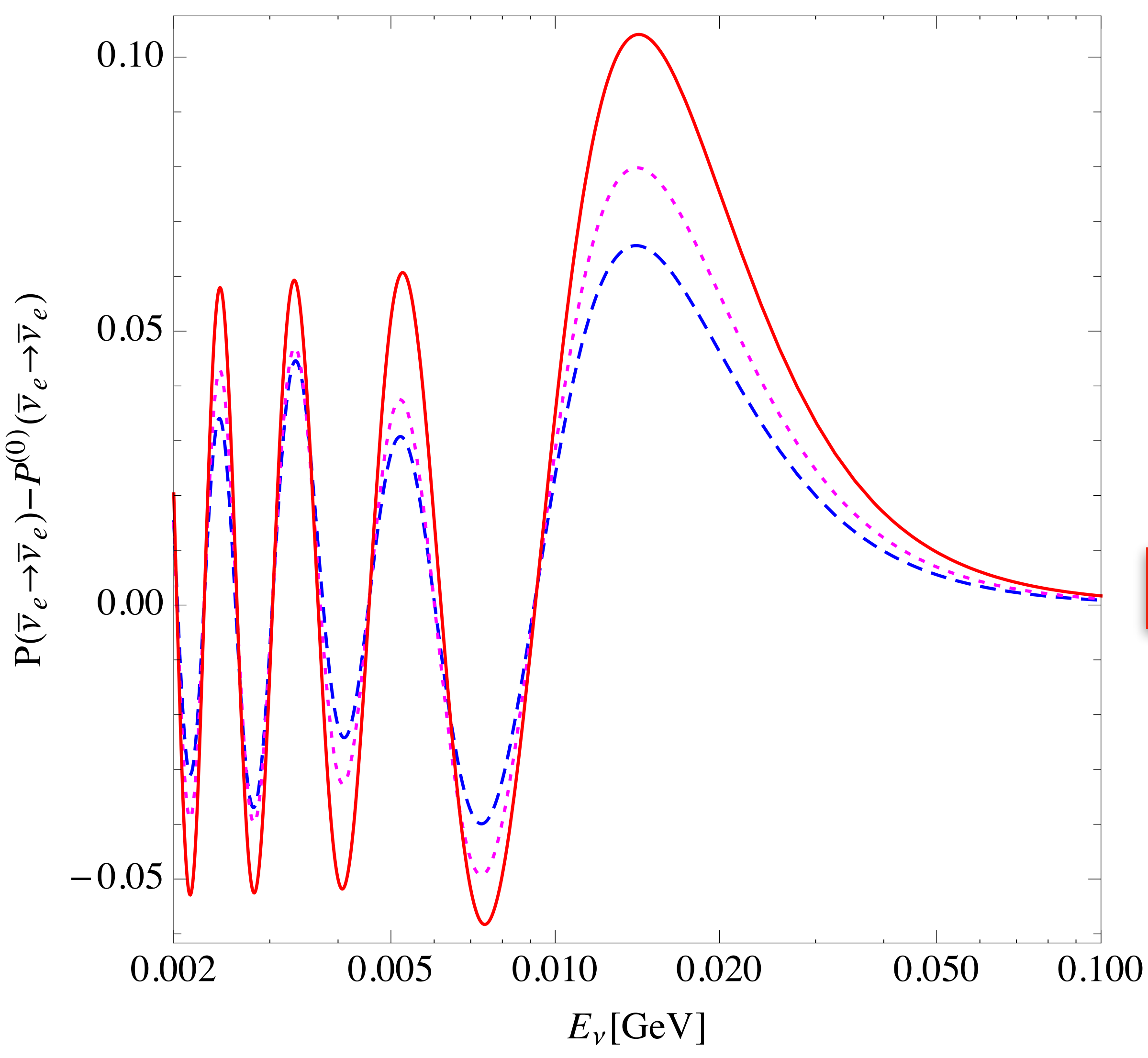


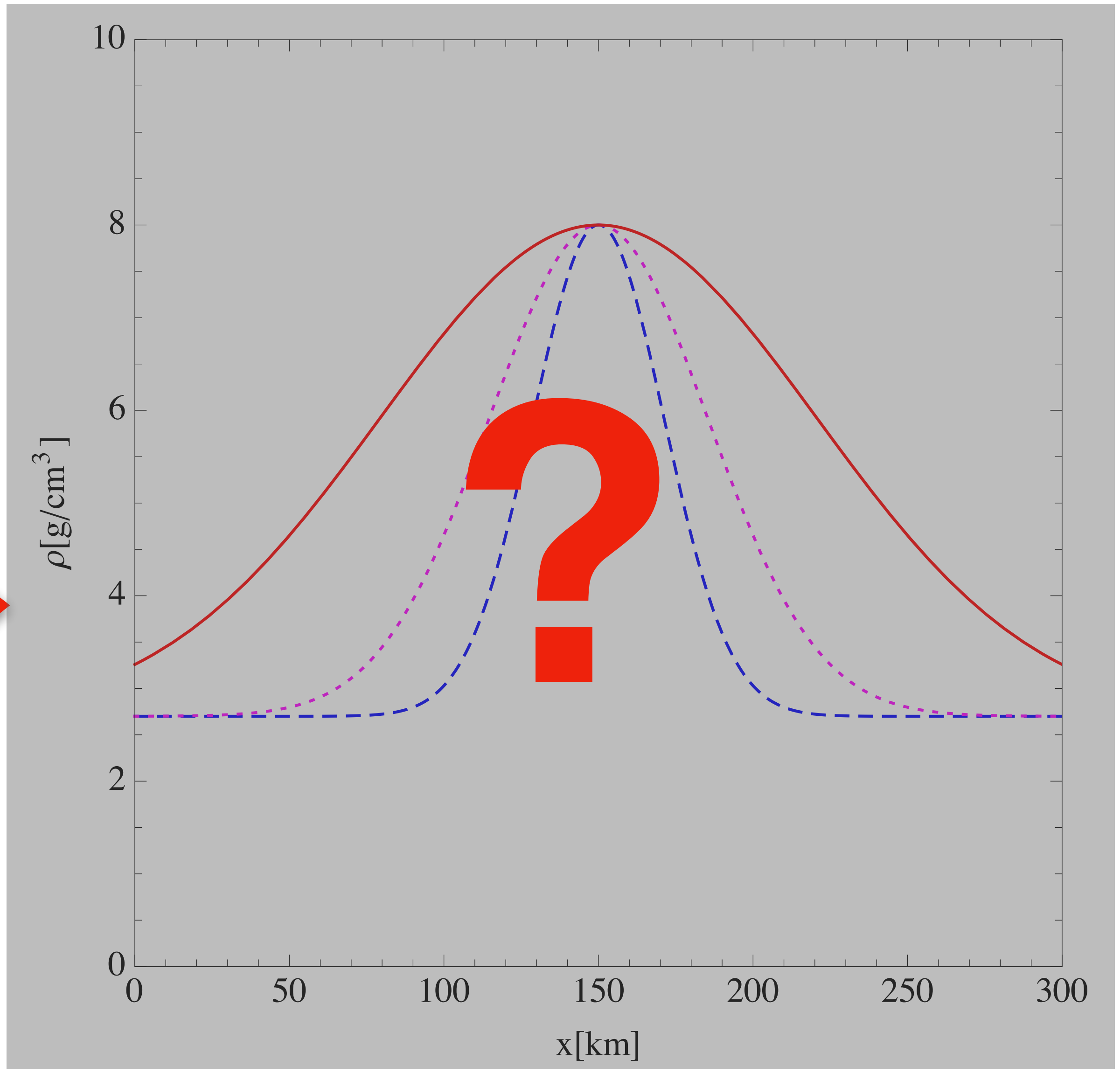

**The pair beam can probe the lump at the 1 σ level as**

$$
\begin{aligned}
&\text{(A)} \quad D_* = 50^{+5.9}_{-5.9}\,\text{km} \quad \text{and} \quad \rho_* = 8.0^{+0.62}_{-0.48}\,\text{g cm}^{-3}\,, \\
&\text{(B)} \quad D_* = 50^{+2.5}_{-2.4}\,\text{km} \quad \text{and} \quad \rho_* = 16^{+0.58}_{-0.53}\,\text{g cm}^{-3}\,, \\
&\text{(C)} \quad D_* = 100^{+8.2}_{-7.1}\,\text{km} \quad \text{and} \quad \rho_* = 8.0^{+0.22}_{-0.21}\,\text{g cm}^{-3}\,,
\end{aligned}
$$

**It is seen that the neutrino pair beam can provide a powerful source for the measurement of the density profile.**

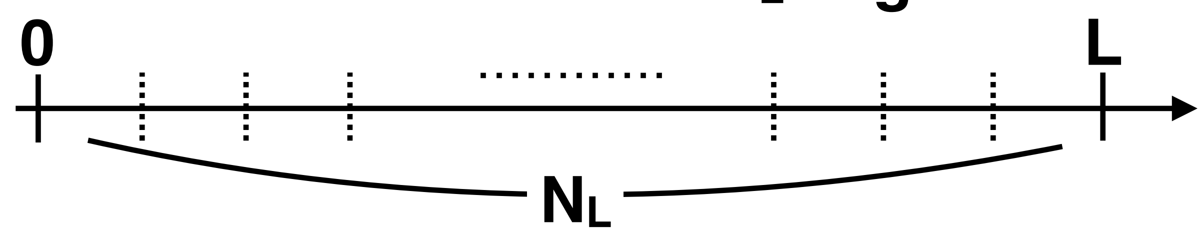
# How reconstruct the entire density profile from the energy spectrum of the neutrino oscillation?



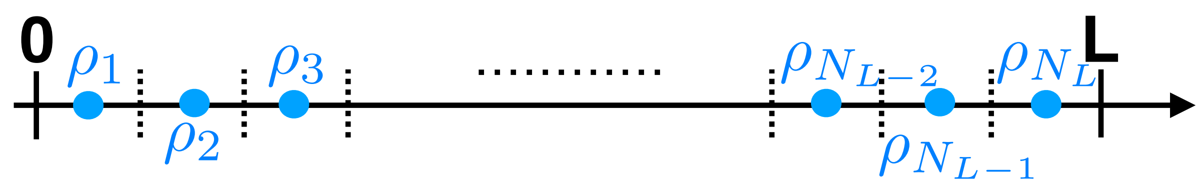



# Reconstruction Method

1. We discretize the neutrino baseline into the $N_L$ segments.

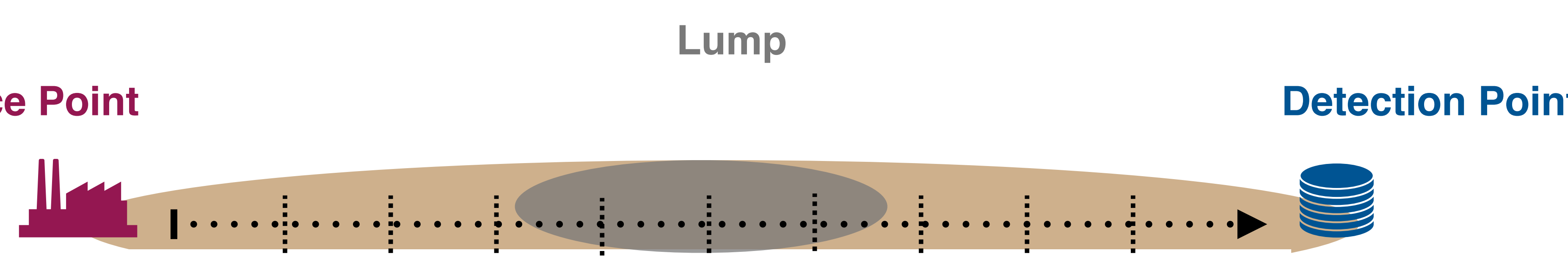



2. We consider the matter densities for these segments as free parameters $\rho_j$ .




$$j = 1, \cdots, N_L$$

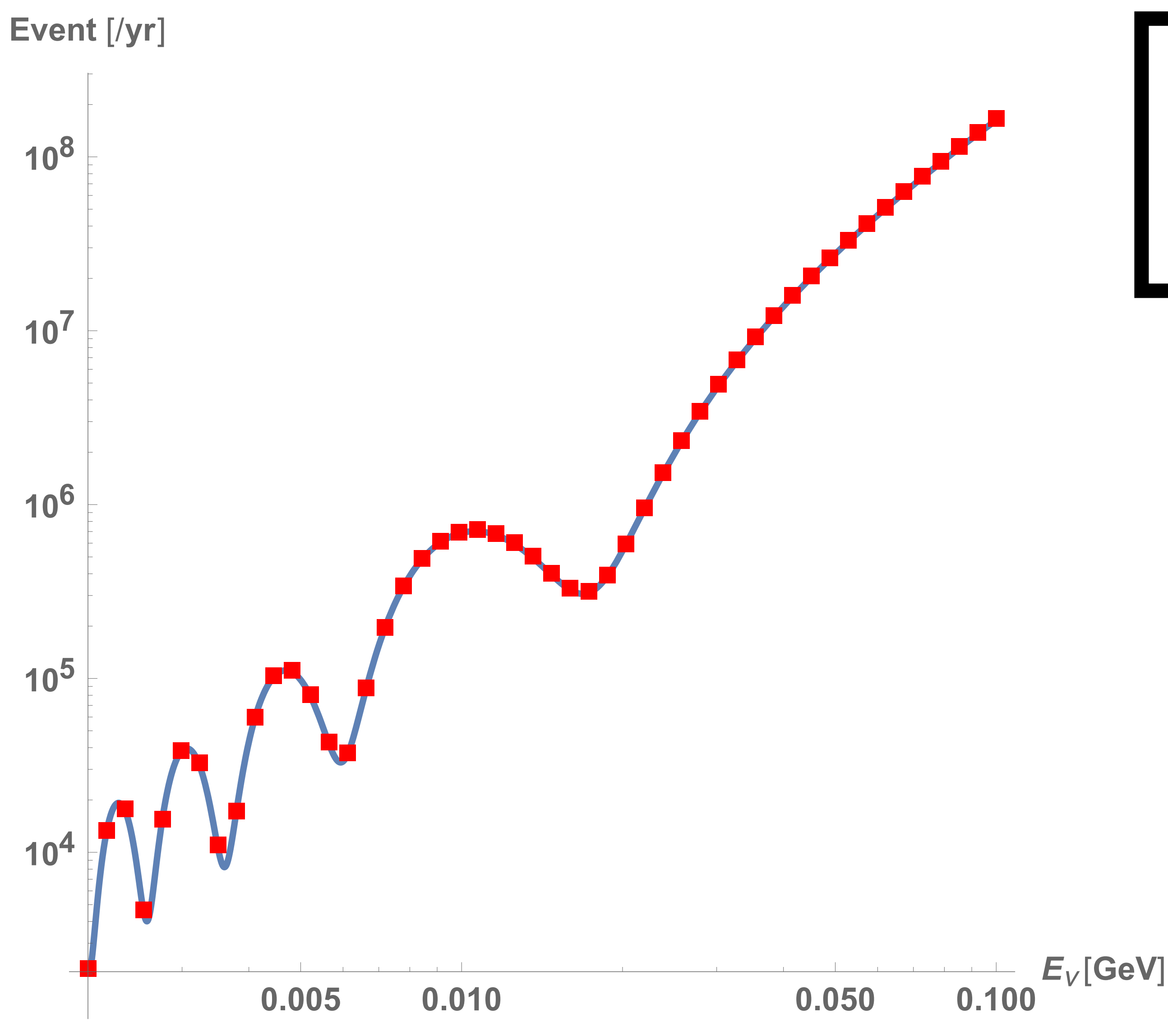
We assume that the each density is constant within each segment.




$$L = 300 \text{ [km]}$$

# Reconstruction Method

**3. We also divide the energy range into the $N_E$ parts, and define the $\chi^2$ function**




$$\chi^2 = \sum_{i=1,N_E} \frac{\left[N^{\rm obs}(E_i) - N^{\rm th}(E_i)\right]^2}{\sigma^2(E_i)}$$

$$\sigma(E_i) = \sqrt{N^{\rm obs}(E_i)}.$$

$$N(E_\nu) \simeq 4.73 \times 10^7 \times P(\bar{\nu}_e \to \bar{\nu}_e; E_\nu) \times \left(\frac{E_\nu}{100\ {\rm MeV}}\right)^{\frac{5}{2}} \left(\frac{\Delta E_\nu}{1\ {\rm MeV}}\right) \left(\frac{300\ {\rm km}}{L}\right)^2 \times \left(\frac{V_d}{10^5\ {\rm m}^3}\right)\left(\frac{T}{1\ {\rm year}}\right).$$

# Reconstruction Method

$$N^{\mathrm{th}}(E_i) = \mathrm{flux} \times P_{\bar{\nu}_e \to \bar{\nu}_e}(E, L) \times \text{detection rate}$$

**Neutrino oscillation probability is calculated from the evolution equation.**

$$i\frac{d}{dx}\vec{A}(x) = [H_0^F + V^F]\vec{A}(x)$$

**Then we assume the relation** $H_0^F > V^F$

**And calculate the oscillation probability by perturbation.**

$$\begin{aligned} P_{\alpha\beta} &= |A^{(0)}_{\beta\alpha} + A^{(1)}_{\beta\alpha} + A^{(2)}_{\beta\alpha} + \cdots|^2 \\ &= \underbrace{|A^{(0)}_{\beta\alpha}|^2}_{\text{0th}} + \underbrace{A^{(0)*}_{\beta\alpha}A^{(1)}_{\beta\alpha} + A^{(0)}_{\beta\alpha}A^{(1)*}_{\beta\alpha}}_{\text{1st}} + \underbrace{|A^{(1)}_{\beta\alpha}|^2 + A^{(0)*}_{\beta\alpha}A^{(2)}_{\beta\alpha} + A^{(0)}_{\beta\alpha}A^{(2)*}_{\beta\alpha}}_{\text{2nd}} + \cdots \end{aligned}$$

0th 1st 2nd

**Ex) perturbation formula at 1st order is written as**

$$P^{(1)}(E_i) \propto \sum \rho(x_j)\left[\sin\left\{\frac{\Delta m^2}{2E_i}L\right\} - \sin\left\{\frac{\Delta m^2}{2E_i}L\right\}x_j - \sin\left\{\frac{\Delta m^2}{2E_i}(L - x_j)\right\}\right]$$

# Reconstruction Method

4. We determine density profile by minimizing the $\chi^2$ function by comparing the observational data $N^{\rm obs}(E_i)$ with given original profile ρ(x) and the theoretical prediction $N^{\rm th}(E_i)$ with unknown parameters $\rho_j$ .

$$\chi^2 = \sum_{i=1,N_E} \frac{\left[N^{\rm obs}(E_i) - N^{\rm th}(E_i)\right]^2}{\sigma^2(E_i)}$$

$$N^{\rm th}(E_i) = {\rm flux} \times P_{\bar{\nu}_e \to \bar{\nu}_e}(E, L) \times \text{detection rate}$$

**Neutrino Oscillation Probability of the perturbation formulae**

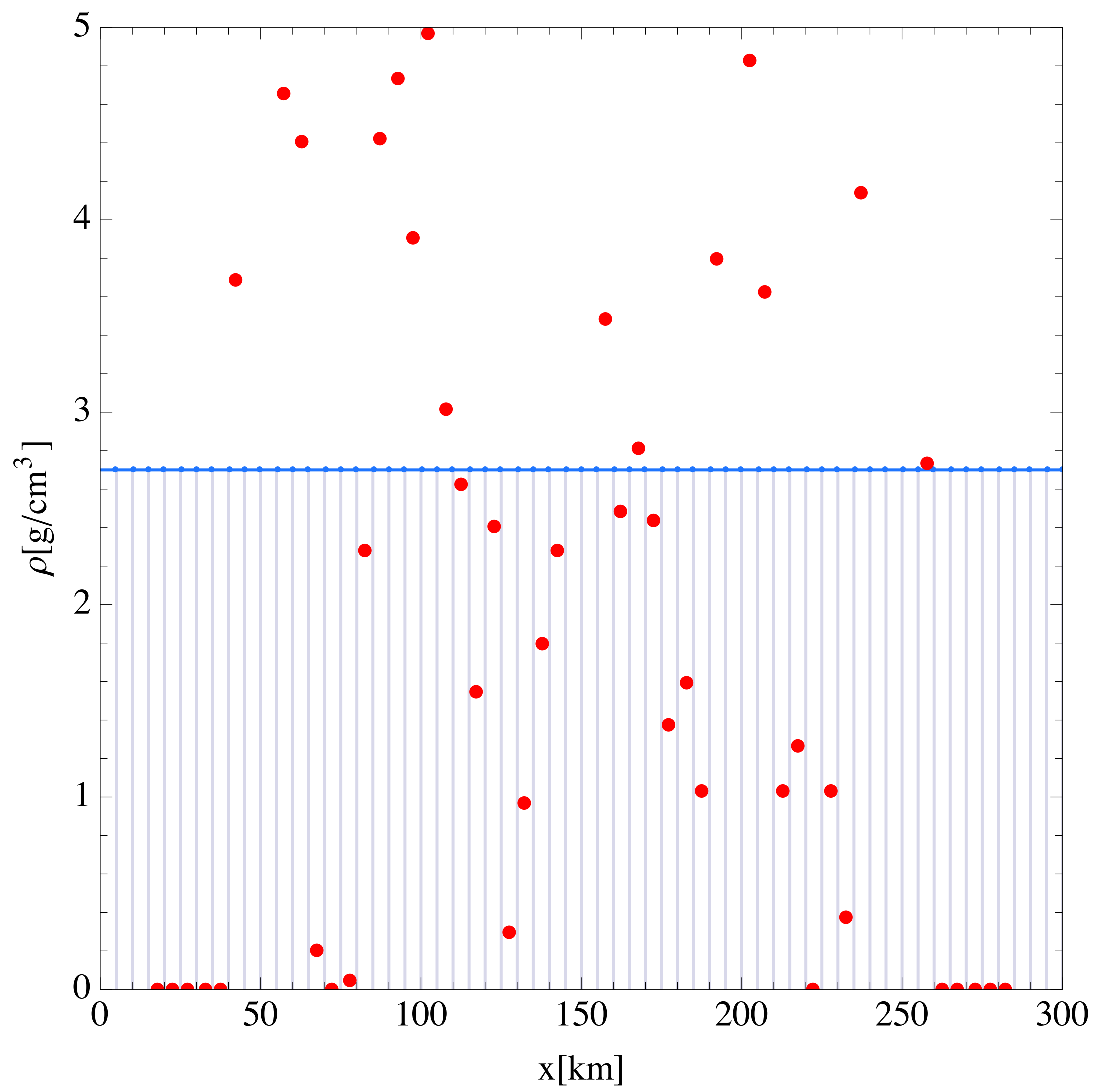
**We find the 2nd order perturbation is important for the successful reconstruction.**

# Results

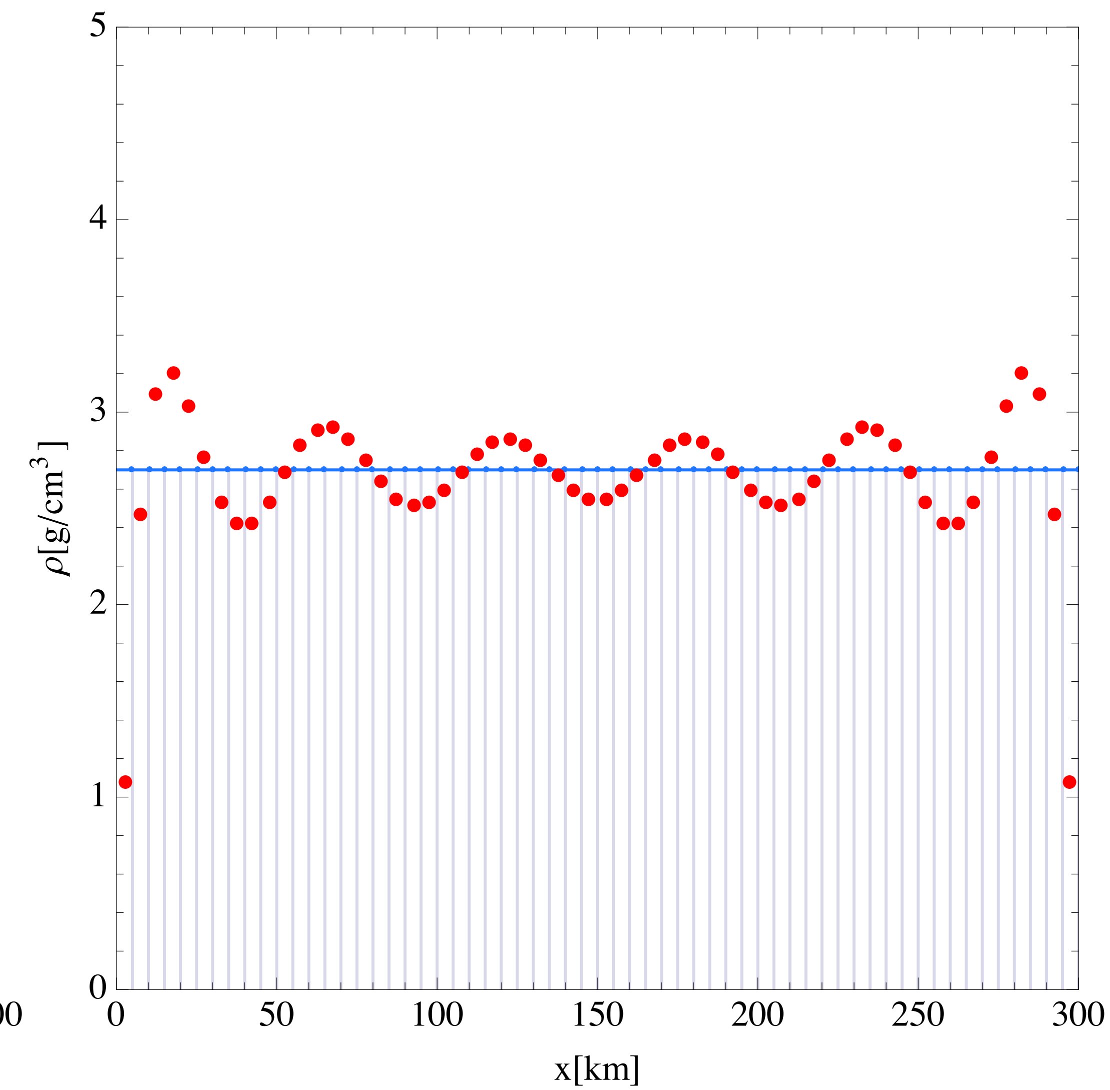
**Reconstruction of 60 segment's densities with 100 energy bins**

$$\bar{\rho} = 2.7\ [\mathrm{g/cm^3}]$$

**Result with using the 1st order formula**




**Result with using the 2nd order formula**




- : Original density profile

• : Reconstructed density profile

# Results

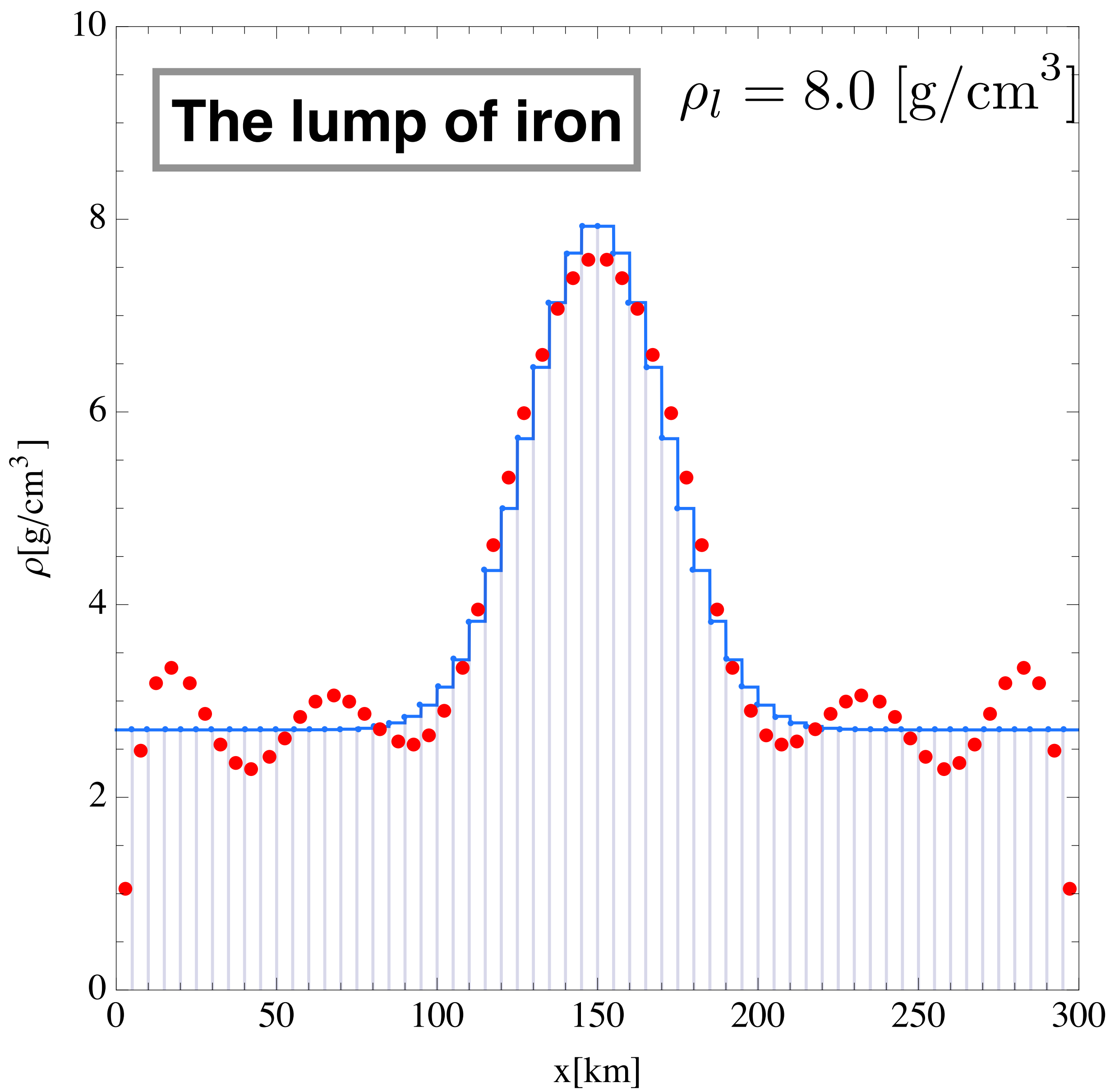
Reconstruction of 60 segment's densities

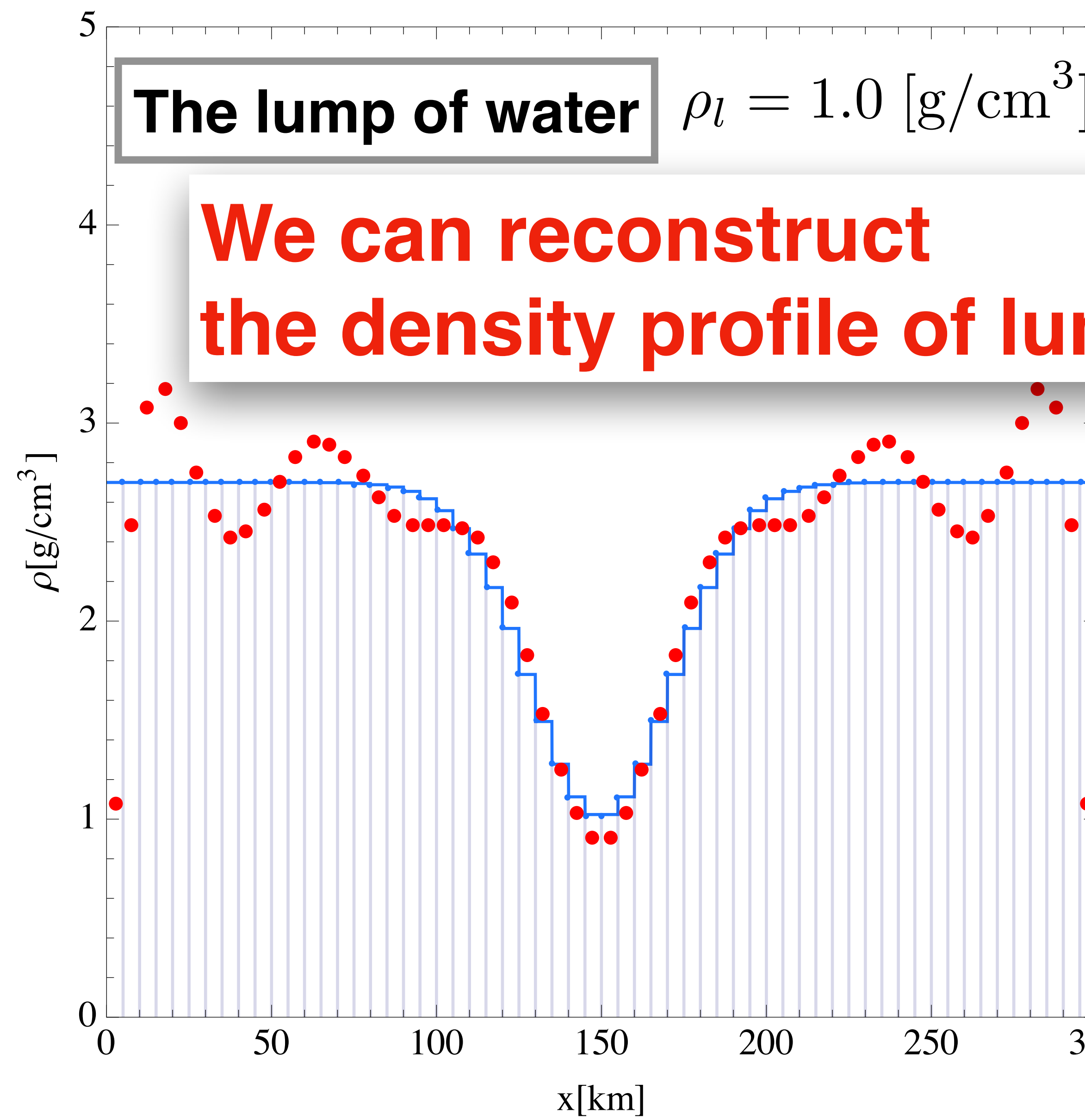
with 100 energy bins

**Original density profile**

$\bar{\rho} = 2.7\ [\mathrm{g/cm^3}]$

$$\rho(x) = \bar{\rho} + (\rho_l - \bar{\rho}) \exp\left[ -\frac{(x - \frac{L}{2})^2}{D_l^2} \right]$$




**We can reconstruct the density profile of lump.**

- : Original density profile

• : Reconstructed density profile

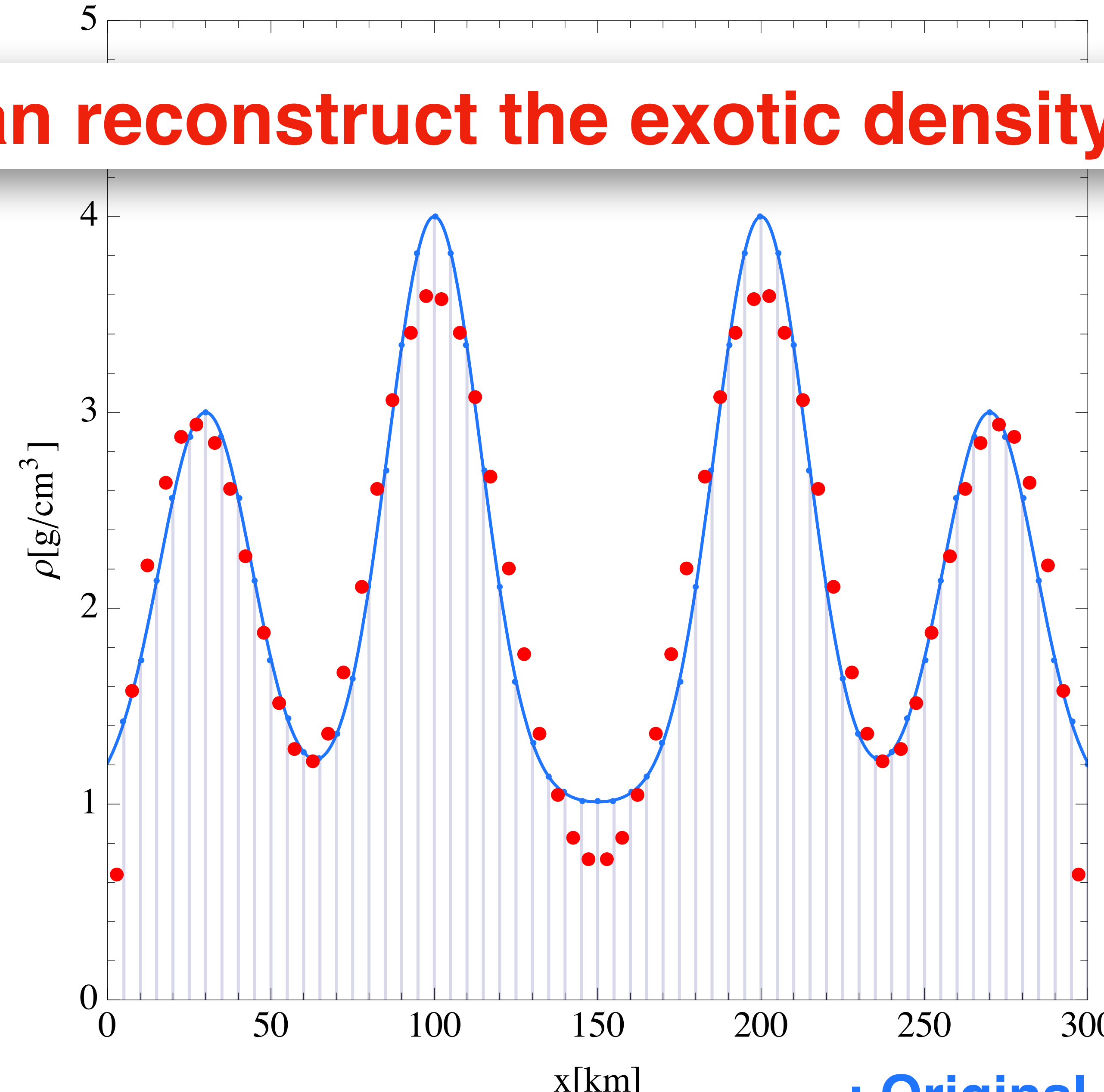
# Results

**Reconstruction of 60 segment's densities**

**by 100 energy bin data**

**using the 2nd order formula**

**4 lump**




**We can reconstruct the exotic density profile.**

**- : Original density profile**

**• : Reconstructed density profile**

# Conclusions

We have investigated the neutrino oscillation tomography by the neutrino pair beam.

**In this talk**

- The neutrino pair beam is a powerful source to the probe of the Earth's interior, especially the structures inside the crust.
- The reconstruction method with the 2nd order perturbation formula is successful tool.
- We believe that these two ingredients give considerable progress toward the realization of the neutrino tomography.