Observation of flavor swap process in supernova II neutrino spectra

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Abstract. We review the concept of quantum flavor swap in a SNII explosion. There will be a specific distortion of the electron neutrino spectrum that can determine if the θ_{13} mixing angle is non-zero. We propose a liquid argon detector to measure the full electron spectrum for very low energy of the 10s of MeV and show how such a detector could be essential to observe the neutrino swap and other neutrino properties.

Neutrino interaction in liquid Argon

Fig. 1 shows the energy spectrum of the neutrino swap indicating that low energy detection is important for an LAr detector. The ICARUS collaboration has studied the low energy detection of solar neutrinos through the process

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

and have shown that the neutrino energy region from about 6 MeV to 18 MeV can be detected. However it is important to go to lower energies to better observe the swapped neutrino spectrum to test the theory. We have therefore studied again the detection of low energy in liquid Argon. In Fig. 4 we show the nuclear levels of the mass 40 system and the processes for both charged currents and neutral currents.

Neutrino interaction in liquid Argon (continued)

- Using the normal ICARUS TPC the group observed that 3 MeV electrons might be detected. However the minimum Gamow Teller resonance is at 4.46 MeV indicating that the electron neutrino energy would be 7.46 MeV.
- In Fig. 5 we show the other possible transitions to the state of 1(+). This is at a much lower energy and such a transition could cover more of the low energy electron neutrino range.
- A clear signature for detection of such a process is the radioactive decay of the state in 0.08ps that can be detected with the scintillation light emitted in the liquid Argon detector. We also note that the extraction of states in could give a signal for the detection of neutral current events.

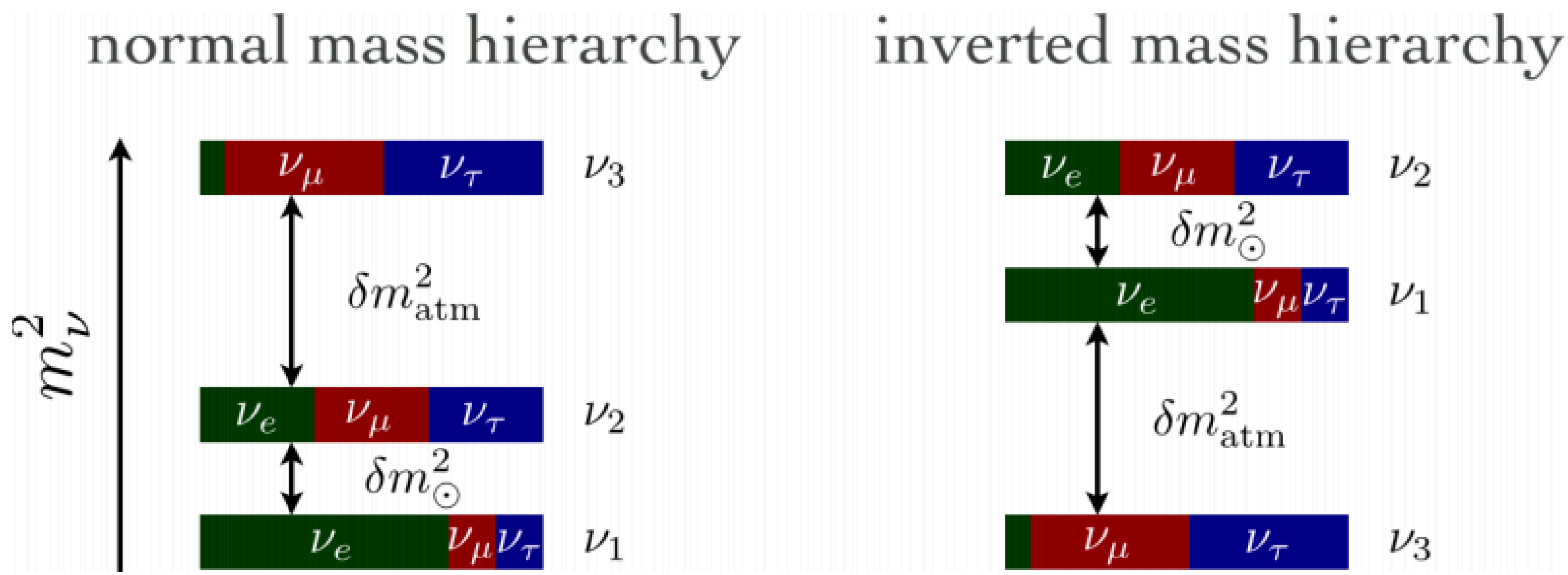
Neutrino Mass: what we know and don't know

We know the *mass-squared* differences:

$$e.g.,\quad \delta m^2_{21} \equiv m^2_2 - m^2_1$$

$$\begin{cases} \delta m^2_{\odot} \approx 8 \times 10^{-5}\,\mathrm{eV}^2 \\ \delta m^2_{\mathrm{atm}} \approx 3 \times 10^{-3}\,\mathrm{eV}^2 \end{cases}$$

We *do not* know the *absolute masses* or the *mass hierarchy*:



Maki-Nakagawa-Sakata matrix

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U_m \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$U_m = U_{23} U_{13} U_{12}$$

$$U_{23} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$U_{13} \equiv \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

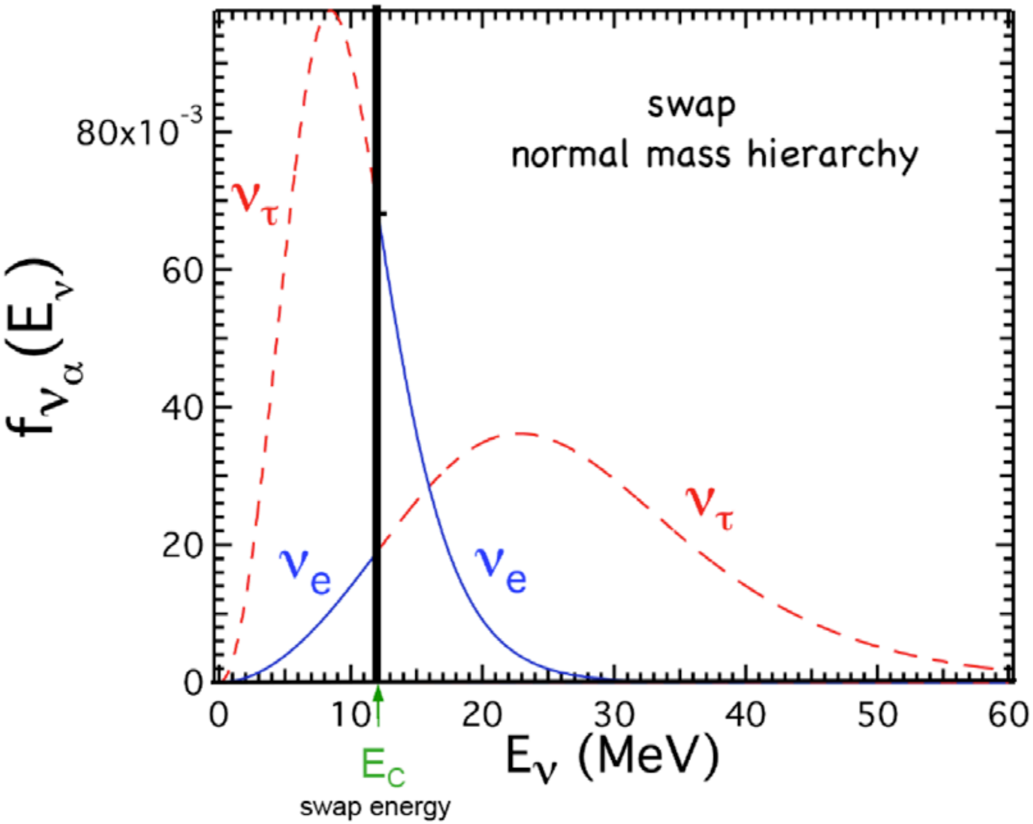
$$U_{12} \equiv \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

4 parameters

we know θ_{12} & θ_{23}

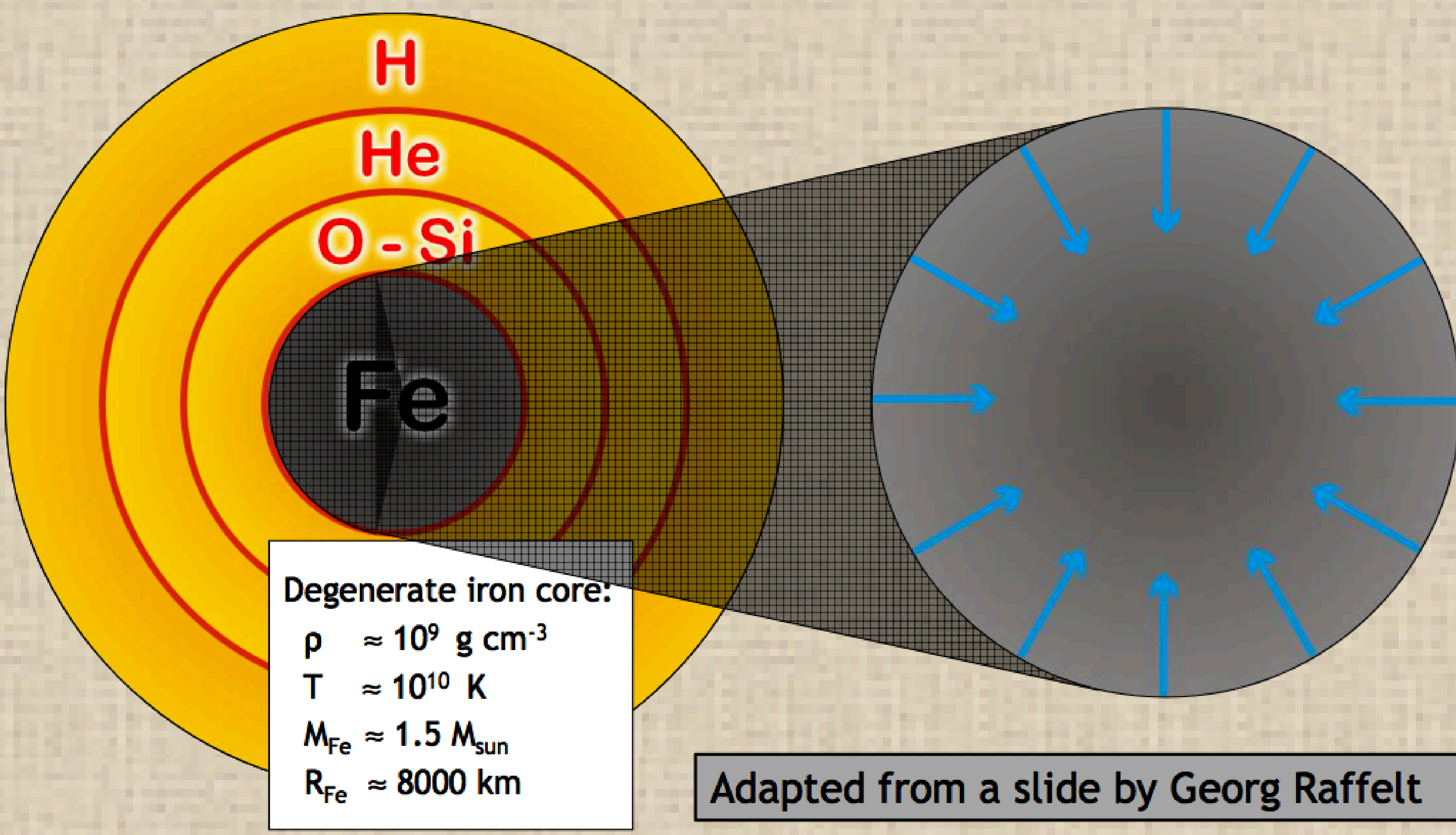
we need δ & θ_{13}

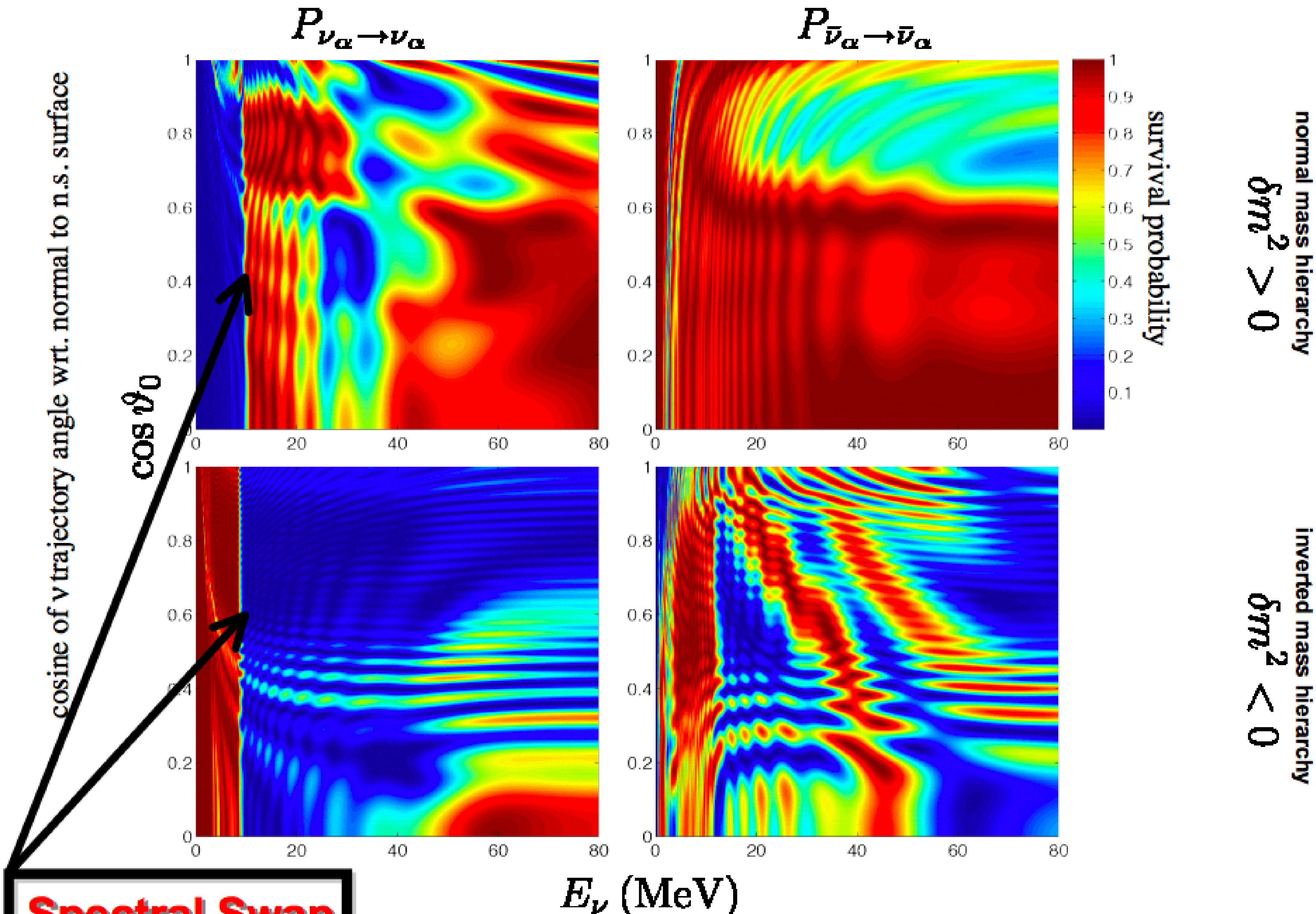
Normal mass hierarchy



SN Explosion and Neutrino Emission

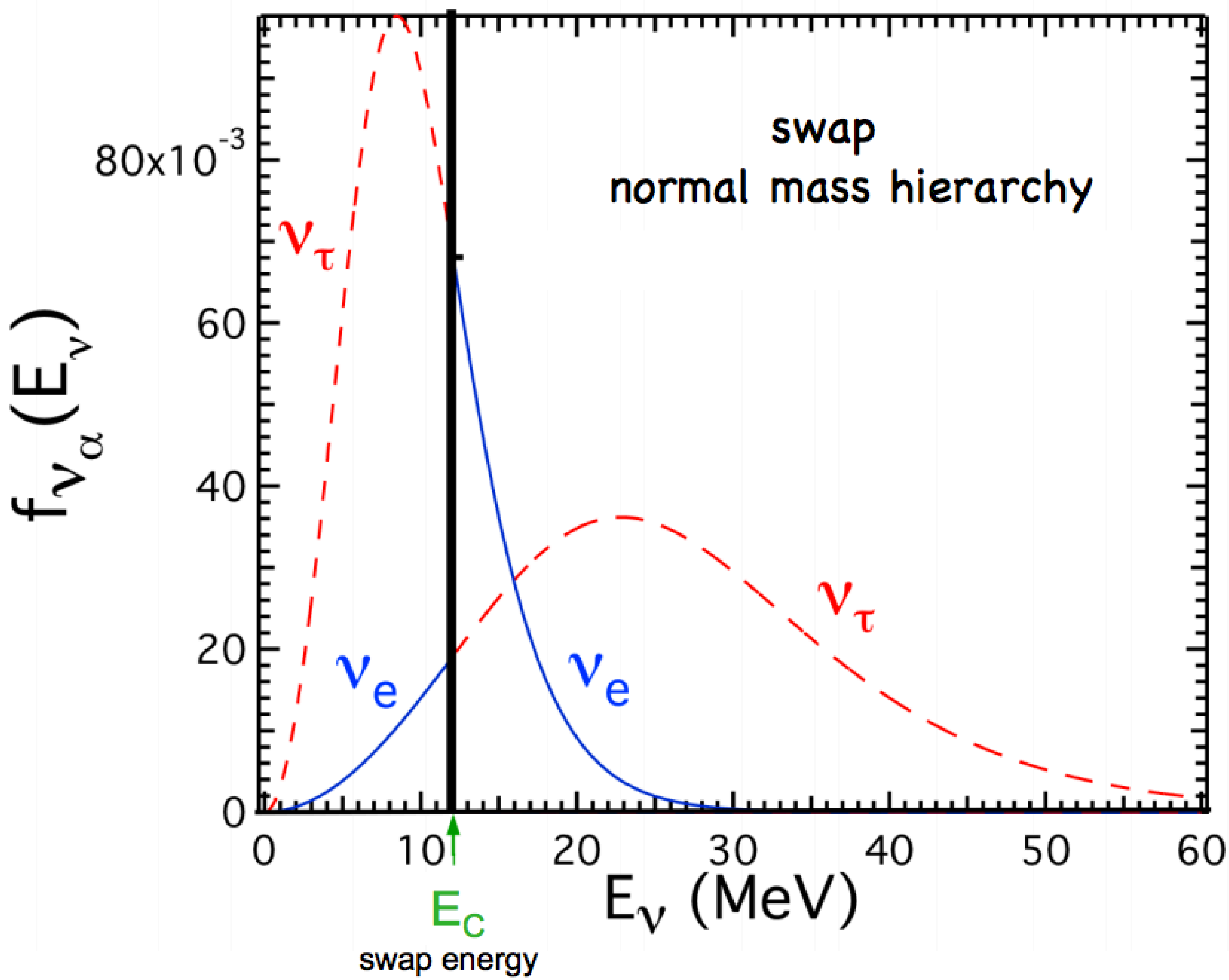
Onion structure | **Collapse (implosion)**





consequences of neutrino mass and quantum coherence in supernovae

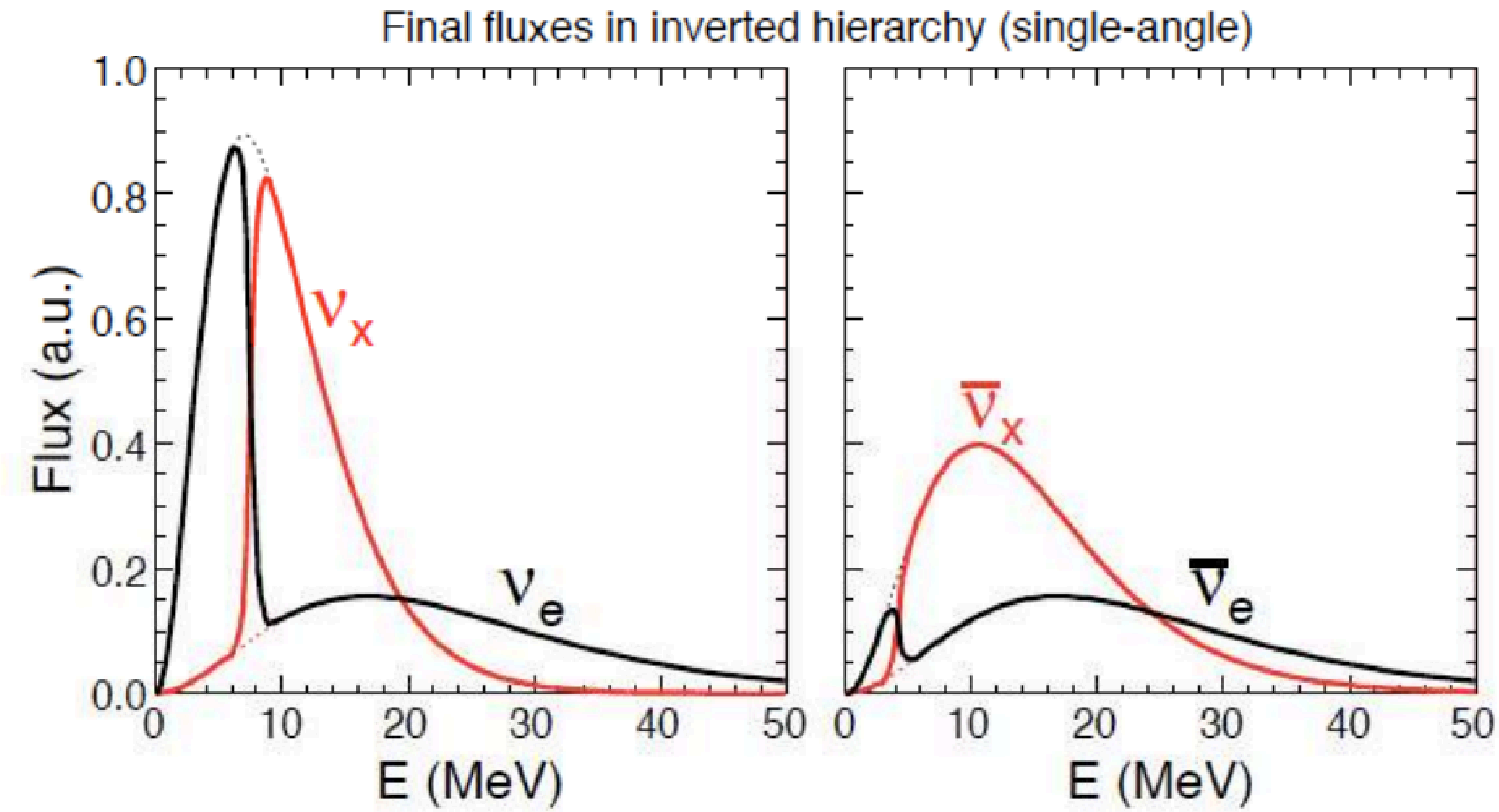
H. Duan, G. M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **97**, 241101 (2006) astro-ph/0606616



swap
normal mass hierarchy
$f_{\nu_\alpha}(E_\nu)$
80x10^-3
60
40
20
0
10
20
30
40
50
60
ν_τ
ν_e
ν_e
ν_τ
E_ν (MeV)
E_C
swap energy

Spectral Swaps: Accretion Phase

Nontrivial Evolution only for Inverted Hierarchy



Fogli, Lisi, Marrone and Mirizzi, arXiv: 0707.1998

Main Detection Channels

- SK-like water Cherenkov detector (30 kt, SN at 10kpc)

$$\bar{\nu}_e p \rightarrow n e^+ : \approx 7000 - 12000^*$$
$$\nu e^- \rightarrow \nu e^- : \approx 200 - 300^*$$
$$\nu_e + ^{16}O \rightarrow X + e^- : \approx 150\text{–}800^*$$

Super-Kamiokande and Icecube are at present our largest detectors for SN neutrinos.

- Scintillation detector

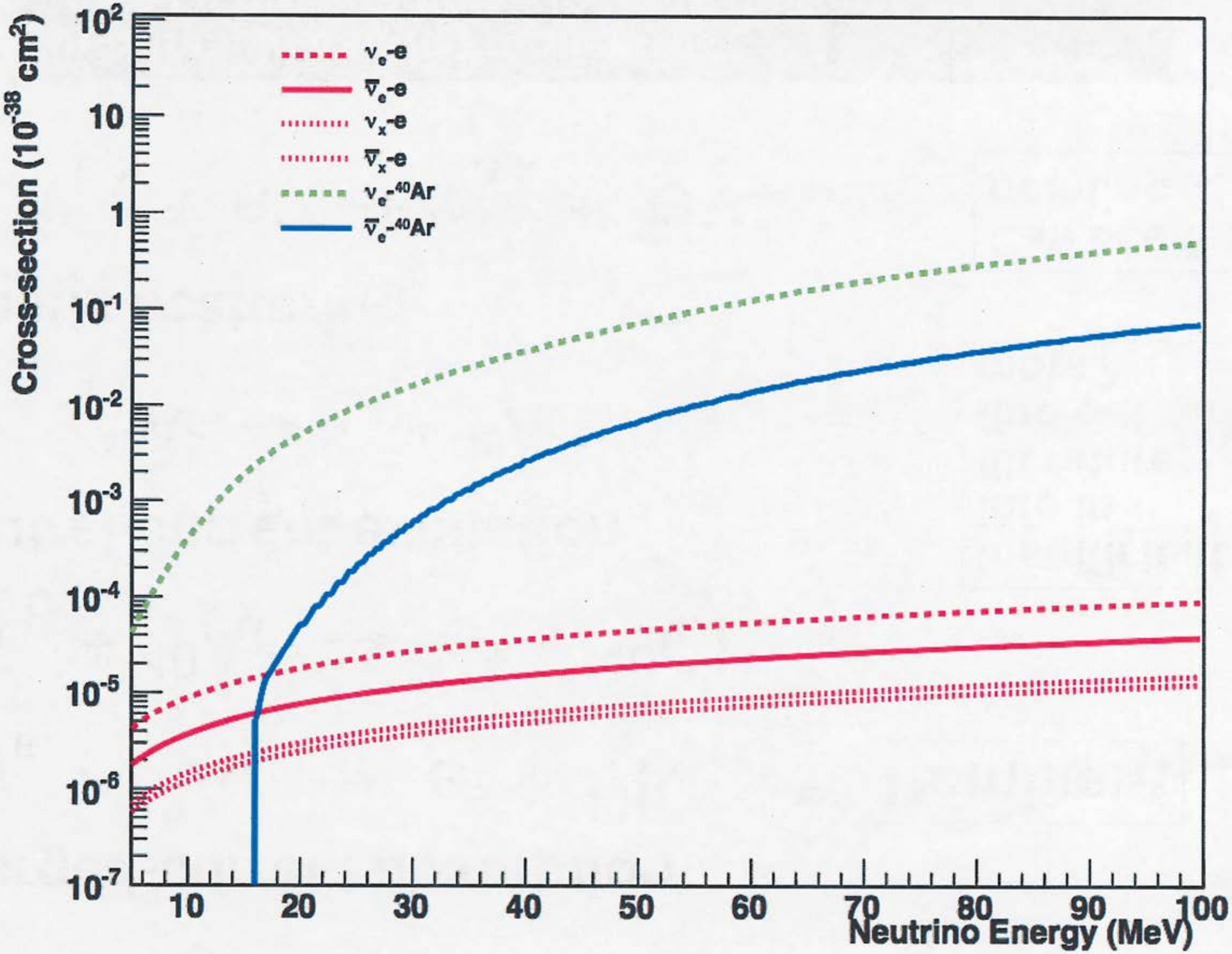
$$\bar{\nu}_e p \rightarrow n e^+$$
$$\nu + ^{12}C \rightarrow \nu + X + \gamma \ (15.11 \text{ MeV})$$

- Liquid Argon detector

$$\nu_e + ^{40}Ar \rightarrow ^{40}K^* + e^-$$

Liquid Argon TPC can see neutrinos, others mostly see antineutrinos

Cross-sections for interactions in argon



Low energy neutrino interactions in argon

Charged-current absorption

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

Dominant

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$

Neutral-current excitation

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

Insufficient info in literature; find out more?

Elastic scattering

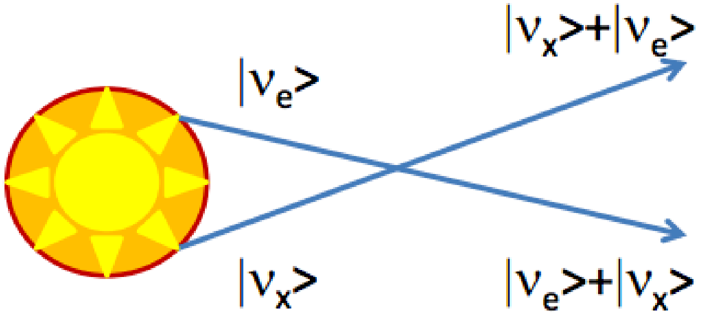
$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

Can use for pointing

- In principle can tag modes with
- deexcitation gammas (or lack thereof)...
- however no assumptions made about this so far

The initial flux is modified by spectral swaps

- Near the Supernova, at high neutrino densities, neutrinos self-interact
- Self-interaction will introduce a collective flavor swap



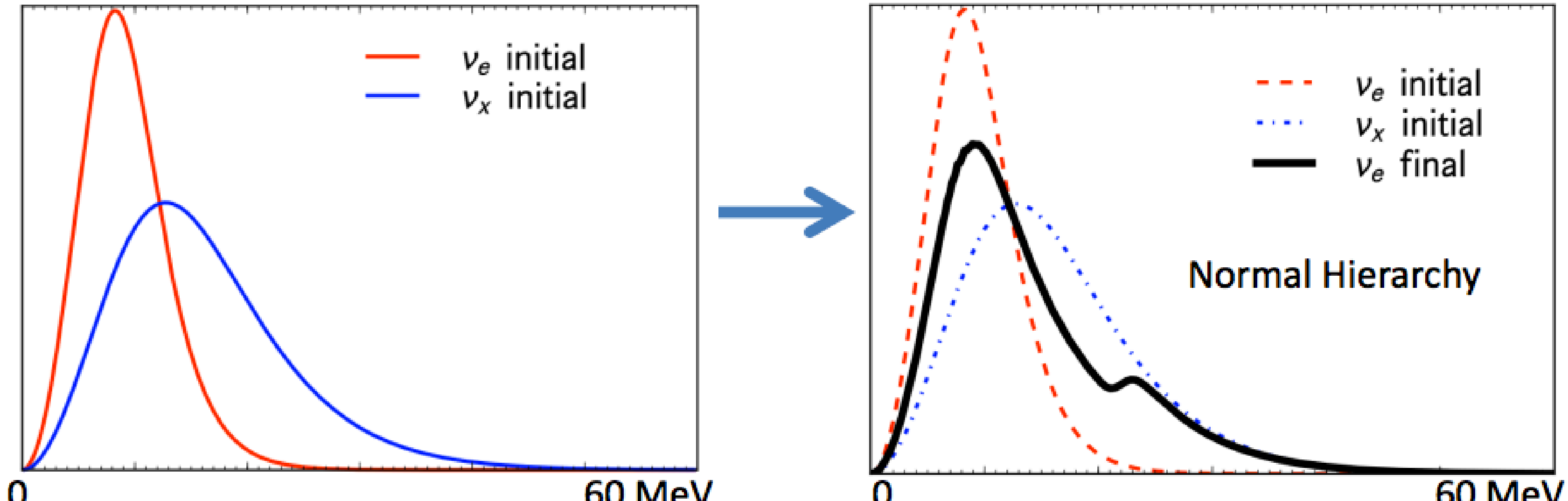


Fig adapted from: Duan and Friedland, Phys. Rev. Lett. 106, 091101 (2011)

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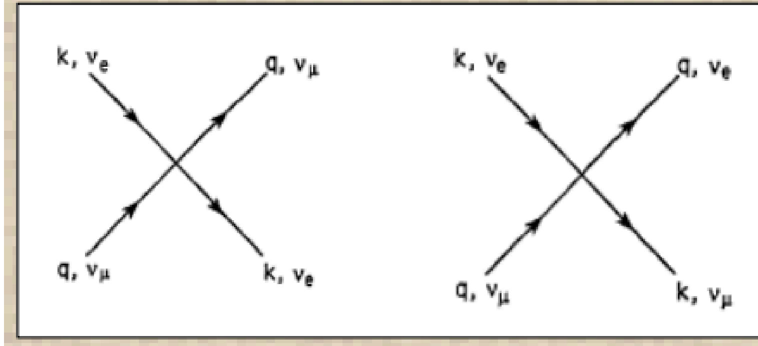
Collective Flavor Conversion

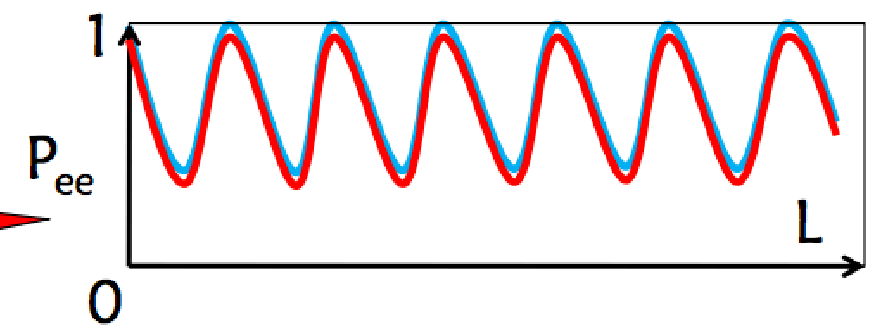


Pantaleone (PLB, 1992)

Neutrino pair-conversions

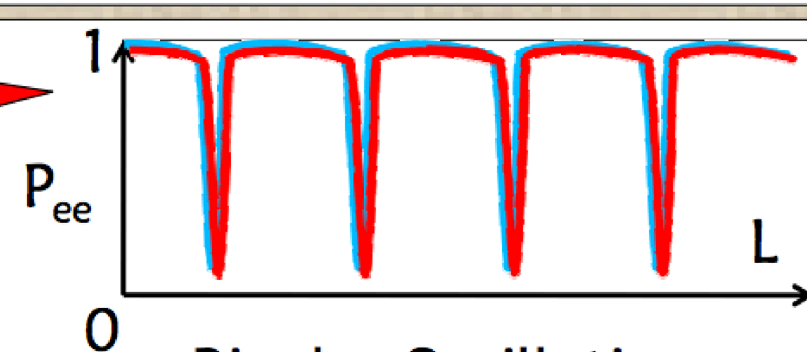
$$\nu_e\bar{\nu}_e \Leftrightarrow \nu_x\bar{\nu}_x$$

Neutrinos of all energies oscillate together.



Synchronized Oscillations

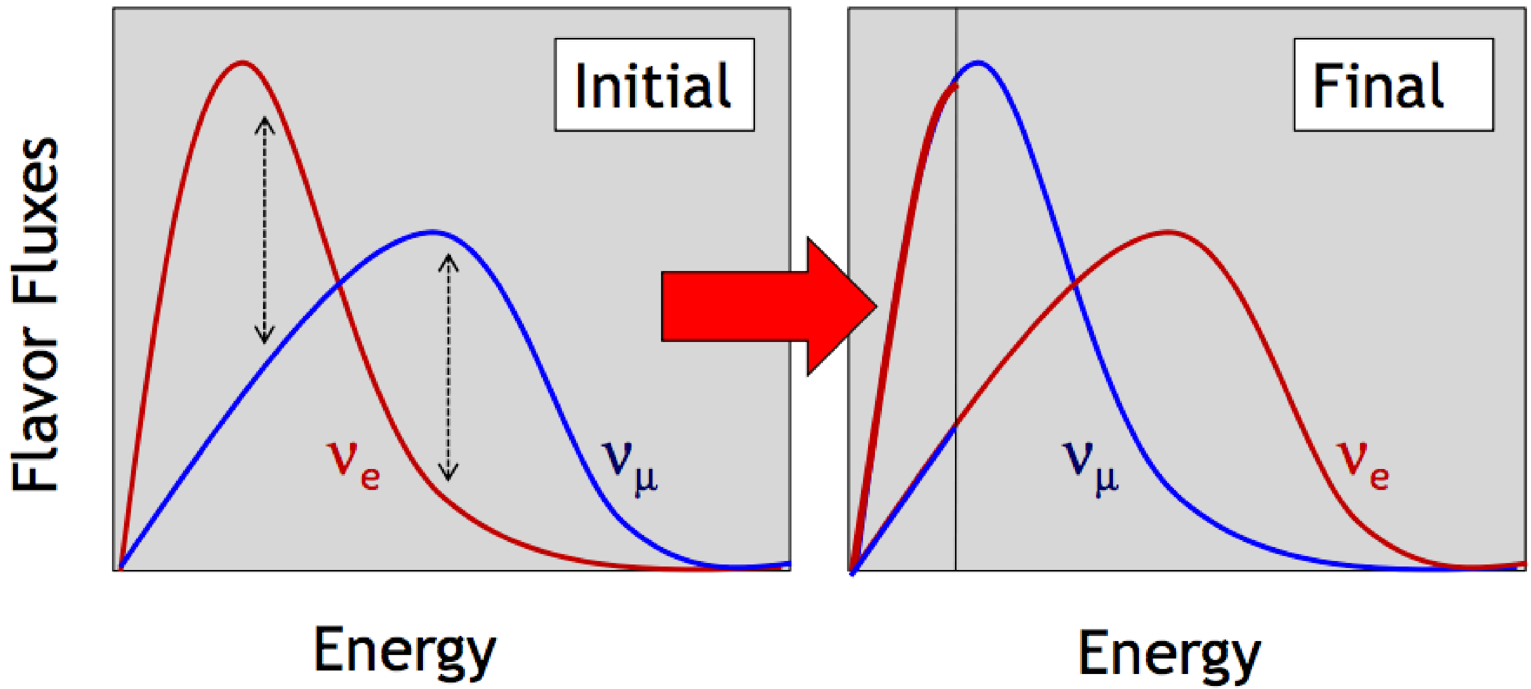
Neutrinos of all energies flip to the lighter mass eigenstate.



Bipolar Oscillations

Collective Flavor Conversion

Instability in Flavor Space → Swap around spectral crossings

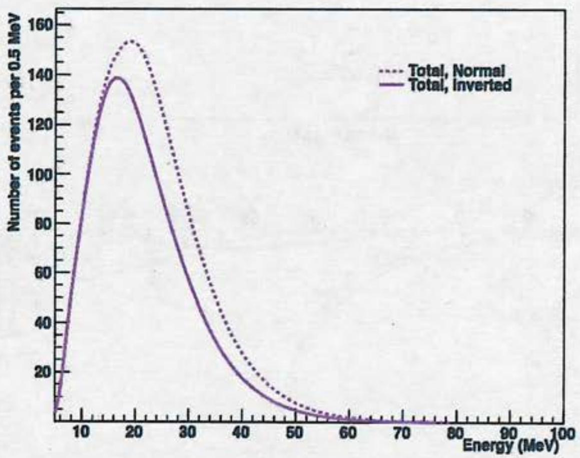


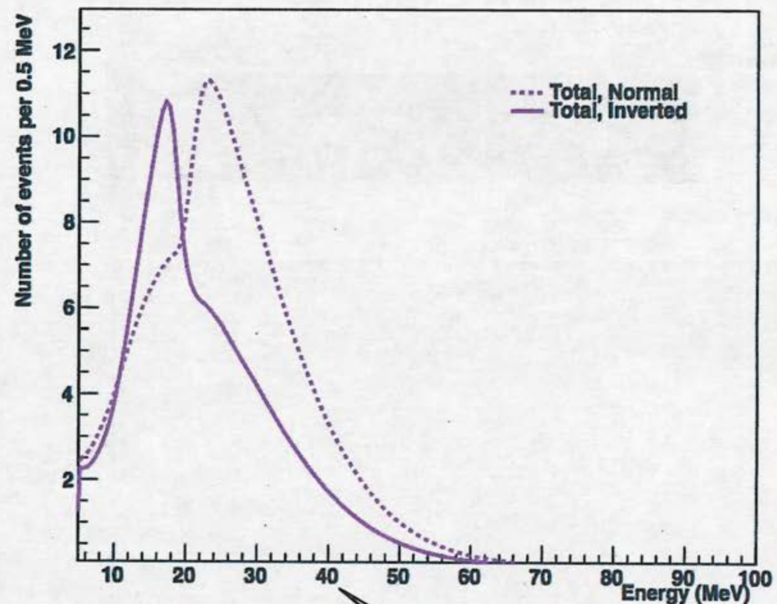
Swap cannot be complete, because of Total Lepton Number Conservation

Observability of oscillation features: example

Can we tell the difference between normal and inverted hierarchies?

(1 second late time slice from Huaiyu Duan flux with 'multi-angle' collective effects)





Differences, but no sharp features in water

LAr shows distinctive features

<u>Caveat</u>: *this is just one model:* need to generalize

Development of liquid Argon detectors to observe the flavor swap

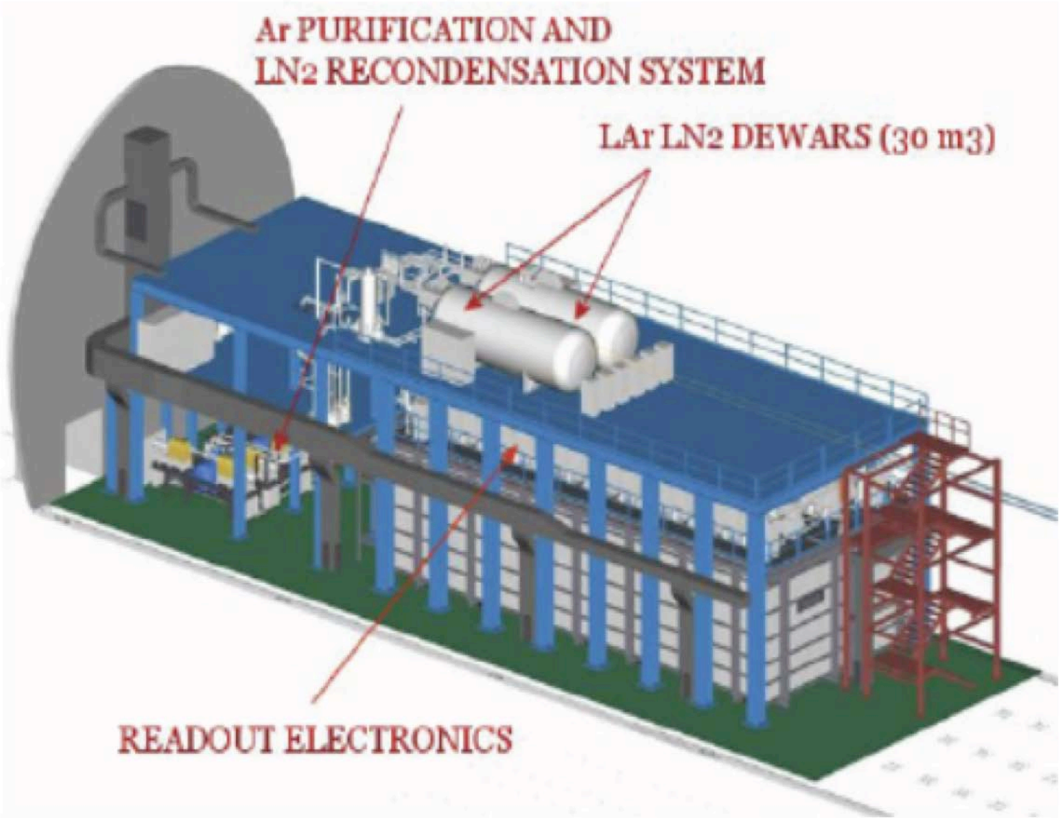
- Since the 1980s there has been a concerted effort to develop large liquid Argon detectors whose signal is detected by the drifting electrons called a TPC (time project chamber). The ICARUS 600 ton detector is now complete at the LNGS laboratory and ready to be filled with liquid Argon. A neutrino beam from CERN will interact in the detector in 2010 [5].

- There has been recent interest in the USA for the DUSEL project such that a 20kt detector is being studied and is in the CD1 phase of the DOE process [6,7]. These two projects will demonstrate the principle of large LAr TPCs and a 20kt detector would be adequate to observe the flavor swap if constructed in a manner to be sensitive. The rates for galactic supernova II for both the current ICARUS and the proposed 20kt detector at DUSEL are given in Table 1.

Rates on liquid Argon TPC for the galactic supernova process

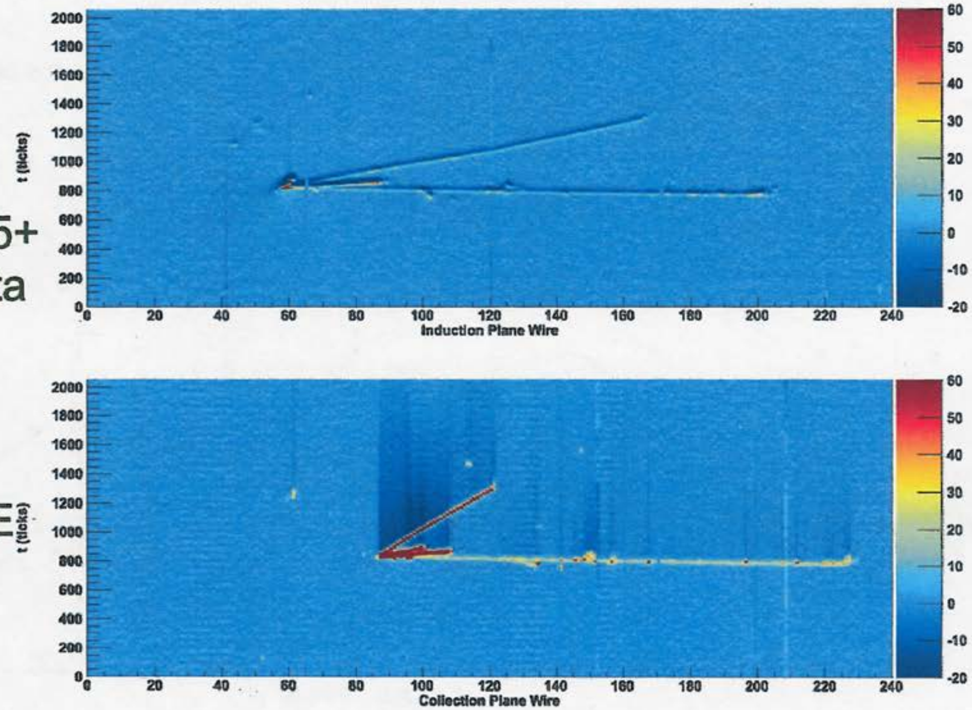
Detector	**Elastic events** $\nu_x + e \rightarrow \nu_x + e$	**Inelastic scatter** $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$
(a) ICARUS at LNGS	~10	~40
(b) 20KT detector at DUSEL	240	~2000 (low threshold)
(c) 100kt detector	1100	~10,000 (low threshold)

Current status of finished ICARUS T600 detector



Chapter 7 – LArTPC Development

- Much R&D over the years
  - ICARUS pioneered this, now taking data w/ T600 in LNGS
  - Vigorous U.S efforts over past 5+ years. ArgoNeuT providing data in the NuMI beam – w/ similar neutrino energy spectrum to LBNE
  - Other prototypes + MicroBooNE coming.



ν_μ CC event in ArgoNeuT

- R&D now is mostly "D"
  - "R" on scintillation photon detection is ongoing
  - In other areas, mainly addressing implementation questions…

Neutrino interaction in liquid Argon (continued)

These kinds of events

$$\nu_x + {}^{40}_{18}Ar \rightarrow {}^{40}_{18}Ar^* + \nu_x$$

could give the crucial total neutrino flux normalization for the supernova II explosion.

If the deexcitation photons can be observed it may be possible to deconvolve and observe the low energy neutrino spectrum of swapped neutrinos. This will need further study.

Prospects for observing low energy neutrons with a LAr detector

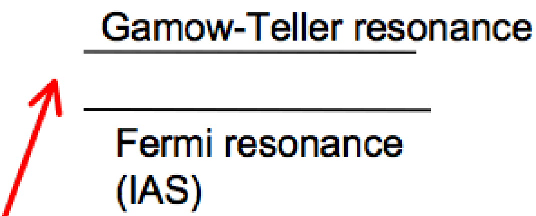
In Fig. 4 and 5 we show the nuclear transitions for the A = 40 system. The normal process studied by the ICARUS team is the

$$^{40}_{18}Ar \rightarrow \, ^{40}_{19}K^{*}$$

Gamow Teller transition. This requires about 4 MeV above ground state and requires about 6 MeV of neutrino energy.

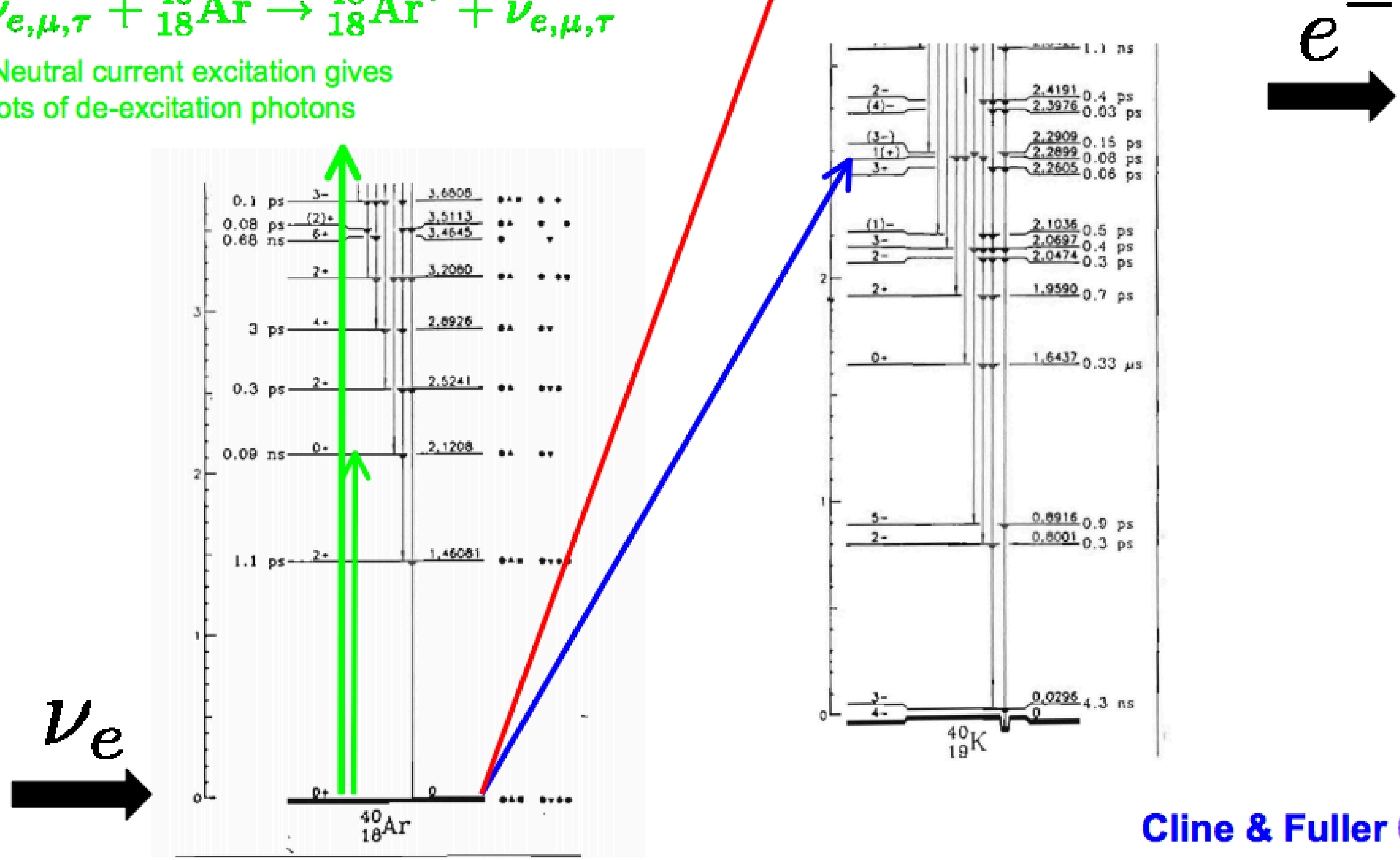
$$\nu_e + {}^{40}_{18}\mathrm{Ar} \rightarrow {}^{40}_{19}\mathrm{K}^* + e^-$$

Charged current capture
gives final state electron
and lots of nuclear de-excitation photons



$$\nu_{e,\mu,\tau} + {}^{40}_{18}\mathrm{Ar} \rightarrow {}^{40}_{18}\mathrm{Ar}^* + \nu_{e,\mu,\tau}$$

Neutral current excitation gives
lots of de-excitation photons



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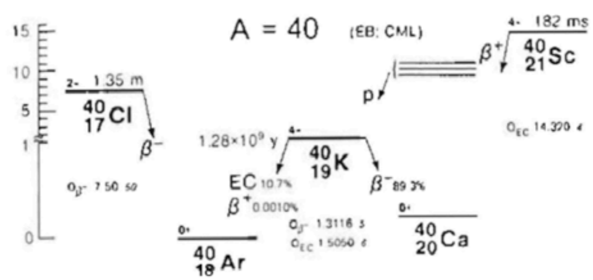
Nuclear physics of Mass 40

Nuclear Physics of Mass 40



Charged current capture on ^{40}Ar : $\nu_e + {}^{40}_{18}\mathrm{Ar} \rightarrow {}^{40}_{19}\mathrm{K} + e^-$

sensitive to neutrino energy
- electron flavor only

Minimum Gamow-Teller Threshold: 3.8 MeV to first 1^+ state
Gamow-Teller resonance: excitation energy E_{GT} ~ 4.46 to 6 MeV
GT-Res Threshold: ~ 6 to 8 MeV

Neutral current excitation of ^{40}Ar : $\nu_{e,\mu,\tau} + {}^{40}_{18}\mathrm{Ar} \rightarrow {}^{40}_{18}\mathrm{Ar}^* + \nu_{e,\mu,\tau}$

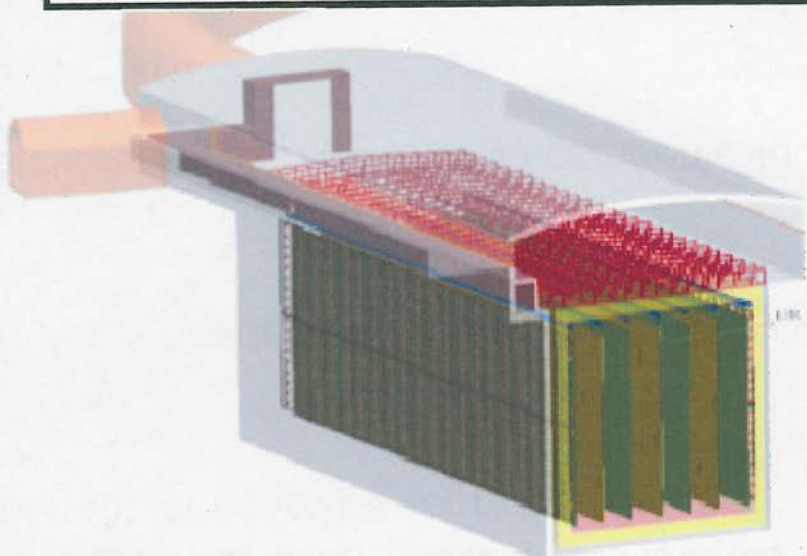
from all flavors-
normalizes flux

Minimum allowed weak threshold: to first 0^+ excited state at 2.12 MeV

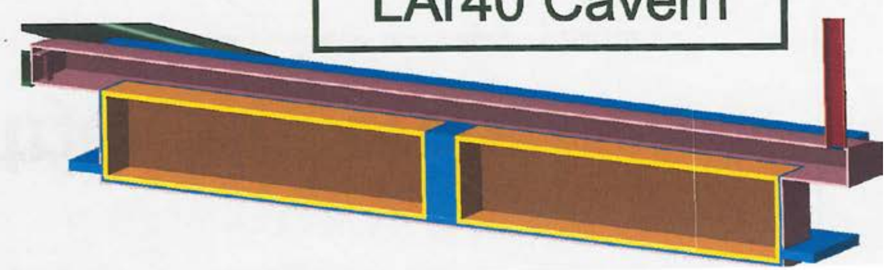
LArTPC Far Detector for DUSEL

- We are proposing:
  - 42 kt (active) / 34 kt (fiducial) Far Detector: "LAr40"
  - Sited at 800L of Homestake mine
  - Two modules (cryostats) end-to-end in a single cavern
  - "Membrane" style cryostat w/ passive insulation; evacuable if need be
  - Modular TPC: Anode wire plane assemblies (APA's) and cathode plane assemblies (CPA's) hung from rails along cryostat roof.
  - CMOS electronics mounted on APA frames & submerged in LAr

One of two 17kt fiducial LArTPC "modules" for LBNE

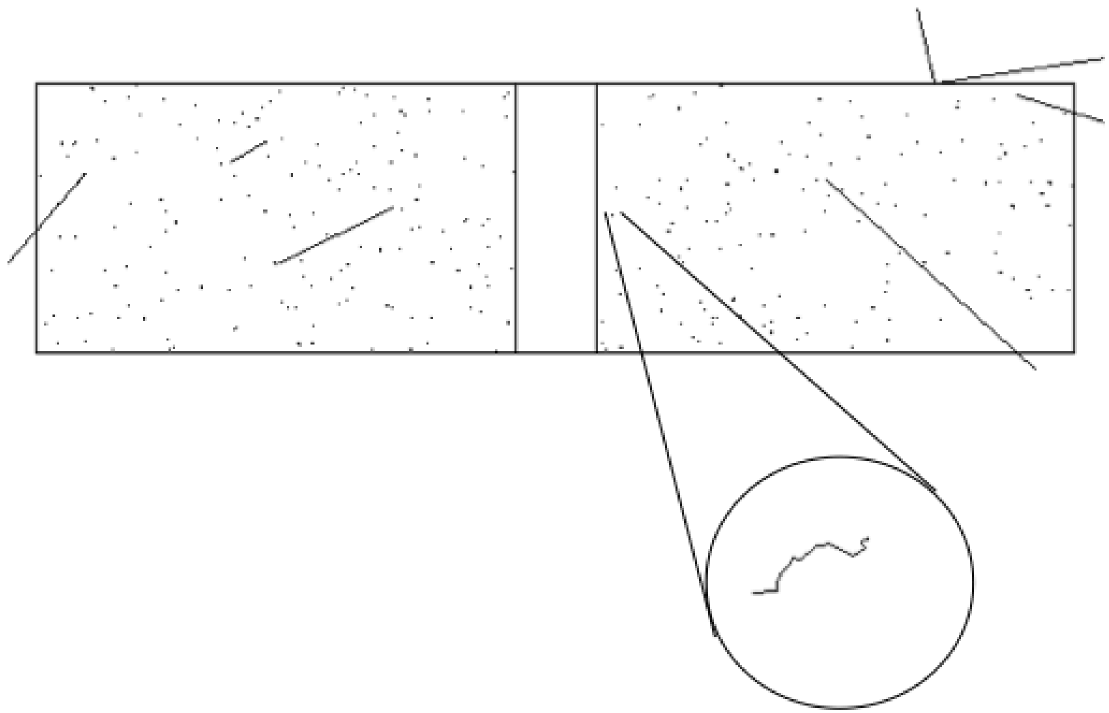


LAr40 Cavern



Low Energy e^- Events in LBNE 10 kTon

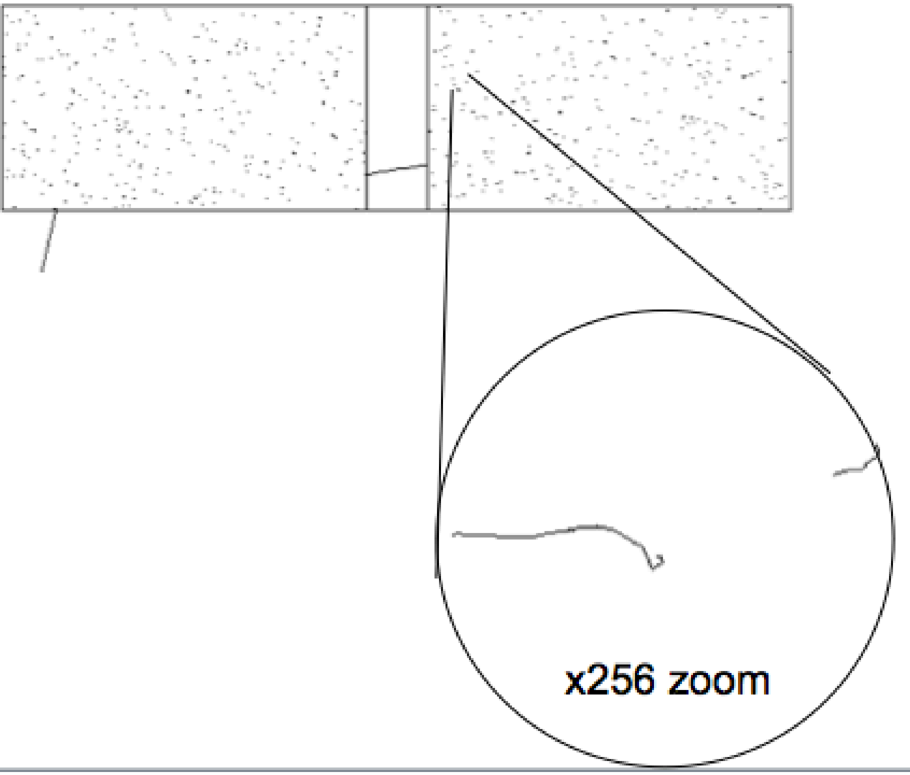
- Two 9.7 kTon LAr Volume of 28.6 m x 16 m x 16 m
- Two 5 kTon fiducial volumes
- 1000 e^- events of 10 MeV



x256 zoom

Low Energy e^- Events in LBNE 10 kTon

- Two 9.7 kTon LAr Volume of 28.6 m x 16 m x 16 m
- Two 5 kTon fiducial volumes
- 1000 e^- events of 20 MeV



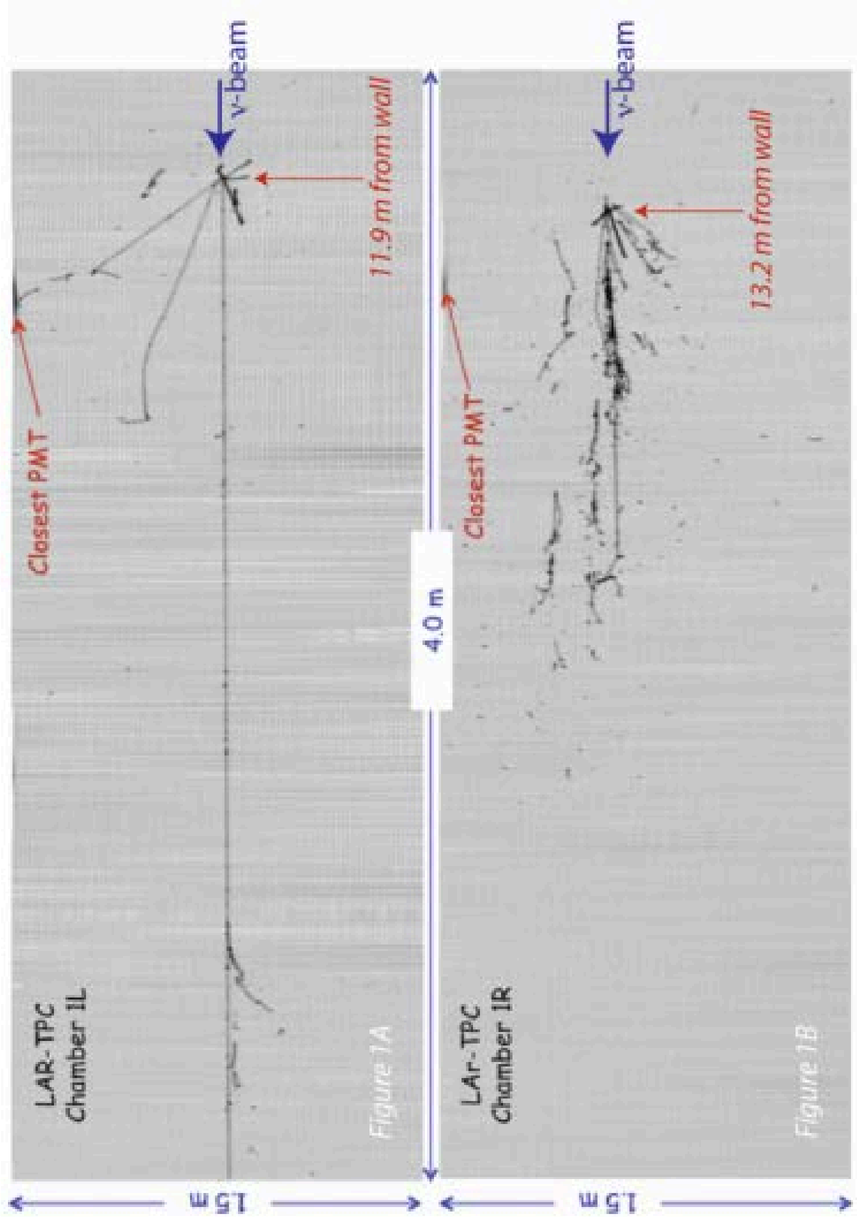


Figure 2: *(a) CC event in the chamber 1L; (b) NC event in the chamber 1R, as visible in the LAr collection view. The actual distances of the vertex from the upstream wall of the detector are indicated. The signal of the closest PMT spontaneously induced on the charge collecting wires is also visible.*

Summary

- 1. The existence of neutrino flavor swap process in SNII explosions provides new information about neutrino properties
- To observe these we need a flavor sensitive detector
- Fortunately the ICARUS TPC with a liquid Argon target has been developed and is operating at the LNGS
- ICARUS is a prototype for the LNBE 10kT Lar detector for Homestake
- We are starting to learn how to analyze the data for a galactic SN explosion