Neutrino Detectors and Neutrinos from Supernovae

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- Where we were in 1987
- What is new since then
- Experimental situation
- Some exciting diagnostics
- Future possibilities
- Summary

Physics of core collapse

- During each stage of nuclear burning (H, He, CNO, Si), each shell of a star establishes hydrostatic equilibrium between gravity and the energy it produces.
- When that stage's fuel is gone, the star contracts, converts gravitational potential energy to heat, and burns the next fuel.
- When the fuel in the core is gone, the core contracts, ... and about once every 10 → 30 years, causes a galactic core-collapse SN

Physics of core collapse--II

- ...and releases its gravitational energy, 99% as neutrinos
  - Gravitational binding energy:

$$E_{Grav} \approx (3/5)\, GM_{NS}^2/R_{NS}$$
$$\approx 3\times10^{53}\ \text{ergs}\ (M_{NS}/1.4M_o)^2\ (10\ \text{km}/R_{NS})$$

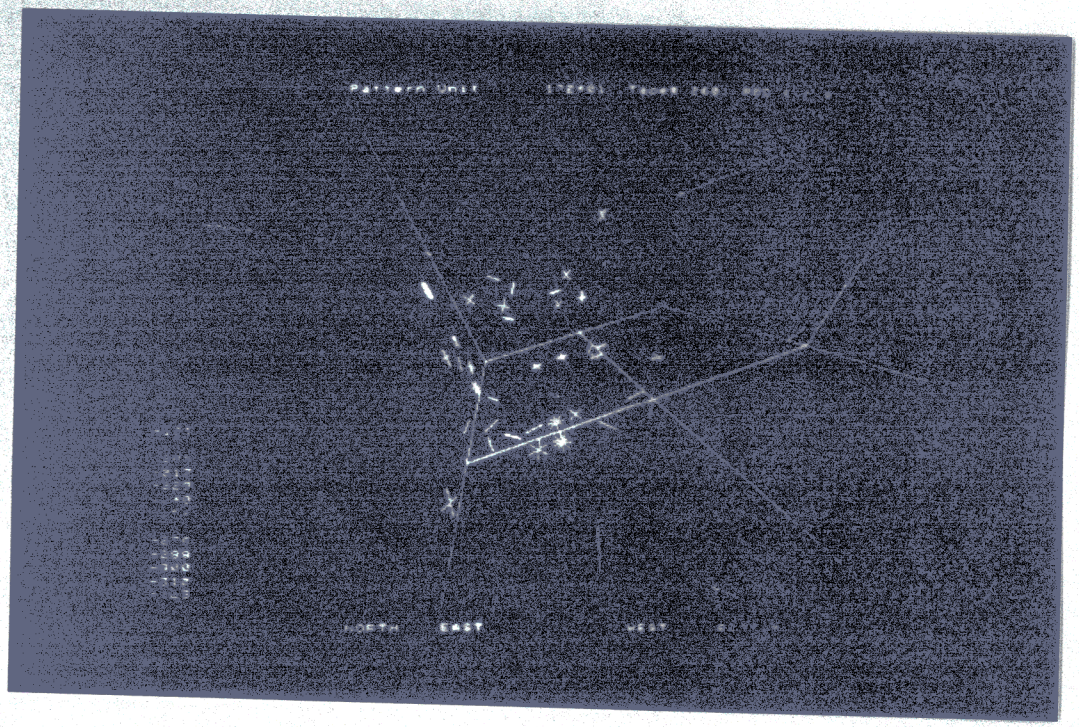
  - Neutrino Diffusion time: $t_\nu \sim 3$ s
- Three stages of ν emission
  - Neutronization: $e^- + p \rightarrow n + \nu_e$
  - Thermal/shock reheating
    - **Thermal emission from neutron star surface in roughly equal amounts of each species**
    - **$\langle E(\nu_e)\rangle \approx 11$ MeV, $\langle E(\bar{\nu}_e)\rangle \approx 16$ MeV, $\langle E(\nu_x)\rangle \approx 25$ MeV**
  - Cooling/nucleosynthesis
    - **Neutron star contracts from 40 km to 10 km**
    - **Time scale ~ 10 s, neutrino-driven r-process nucleosynthesis?**

Supernova ν shopping list

Particlephysical	Astrophysical
Direct (TOF) meas. of m_ν	ν opacities + W.I.
spin/flavor resonance flip + ν mag. moment	ν driven convection shock wind ⋮
Matter enhanced osc. SN + Earth	ν driven nucleosynthesis creation r process destruction ν induced fission
θ_{13} effects, mass heirarchy	
majoron/axion/anyon emission	star Formation constraints
sterile ν	B.H. Formation
Extra dim. space-time	Fermion geodesic = Boson geodesic
Lorentz invariance violation (or not)	

Situation in 1987

- Protons were hoped to decay
  - Thus several large nucleon decay detectors were operating
- Neutrinos were hoped to oscillate
  - Earliest hints of the 'atmospheric neutrino anomaly' and the 'solar neutrino problem'
- A star in the LMC decided to implode



We have been 'data starved' since then

Neutrino physics

- Post Super-K, SNO, KamLAND, we now know that neutrinos oscillate flavors

For two neutrino species ν_e and ν_μ we have:

$$|\nu_e\rangle = |\nu_1\rangle \cos\theta + |\nu_2\rangle \sin\theta$$
$$|\nu_\mu\rangle = -|\nu_1\rangle \sin\theta + |\nu_2\rangle \cos\theta$$

where ν_1 and ν_2 are the mass eigenstates.

In a weak decay one produces a definite weak eigenstate

$$|\nu(t=0)\rangle = |\nu_e\rangle .$$

At a later time the probability of the final state will be:

$$|\nu(t)\rangle = |\nu_1\rangle e^{-iE_1 t}\cos\theta + |\nu_2\rangle e^{-iE_2 t}\sin\theta$$

The survival probability is:

$$P(\nu_e \to \nu_e; L) = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.27\ \Delta m^2_{eV}\ L_{km}}{E_{GeV}}\right).$$

Oscillation Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \sim 1/\sqrt{2} & \sim 1/\sqrt{3} & \sim 0 \\ \sim 1/\sqrt{2} & \sim 1/\sqrt{3} & \sim 1/\sqrt{2} \\ \sim 1/\sqrt{6} & \sim 1/\sqrt{3} & \sim 1/\sqrt{2} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} \nu_3 \\ \vdots \end{pmatrix}$$

near maximal

$$\nu_e \longleftrightarrow \nu_\mu \longleftrightarrow \nu_\tau$$

near minimal

$$\Delta m^2_{12} \simeq 7 \cdot 10^{-5}\,\mathrm{eV}^2$$

$$\Delta m^2_{23} \simeq 2 \cdot 10^{-3}\,\mathrm{eV}^2$$

$$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$$

Oscillations in SN

- Due to huge density run from core to envelope, matter-enhancement of atmospheric and LMA oscillation occurs
  - Assuming $\theta_{13} \neq 0$, it is likely that $\nu_e \leftrightarrow \nu_\tau$ oscillations will be nearly maximal
- Thus we should generally expect the ν_e spectrum to be 'hot', the ν_x spectrum to be 'cool'

Supernova neutrino detection

- ‘Traditionally’ water-Cherenkov & scintillation detectors primarily see CC

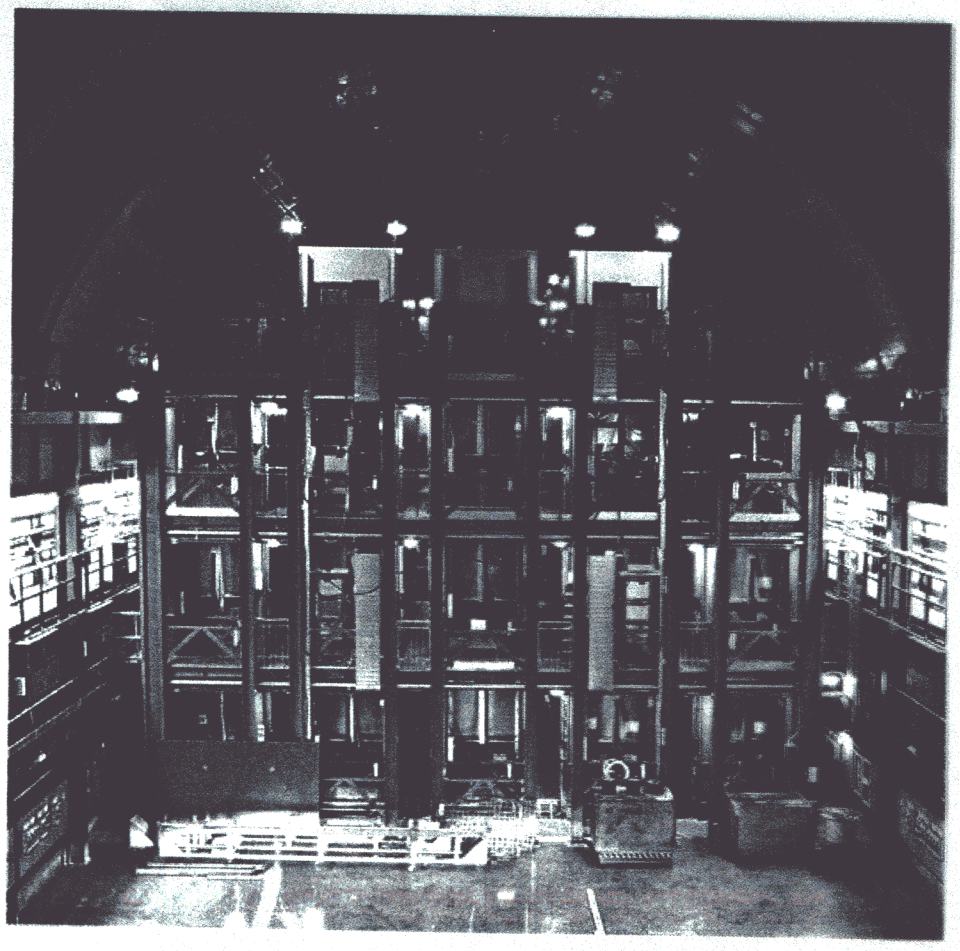
$$\underline{\nu}_e + p \rightarrow e^+ + n$$

(or its nuclear equivalent)

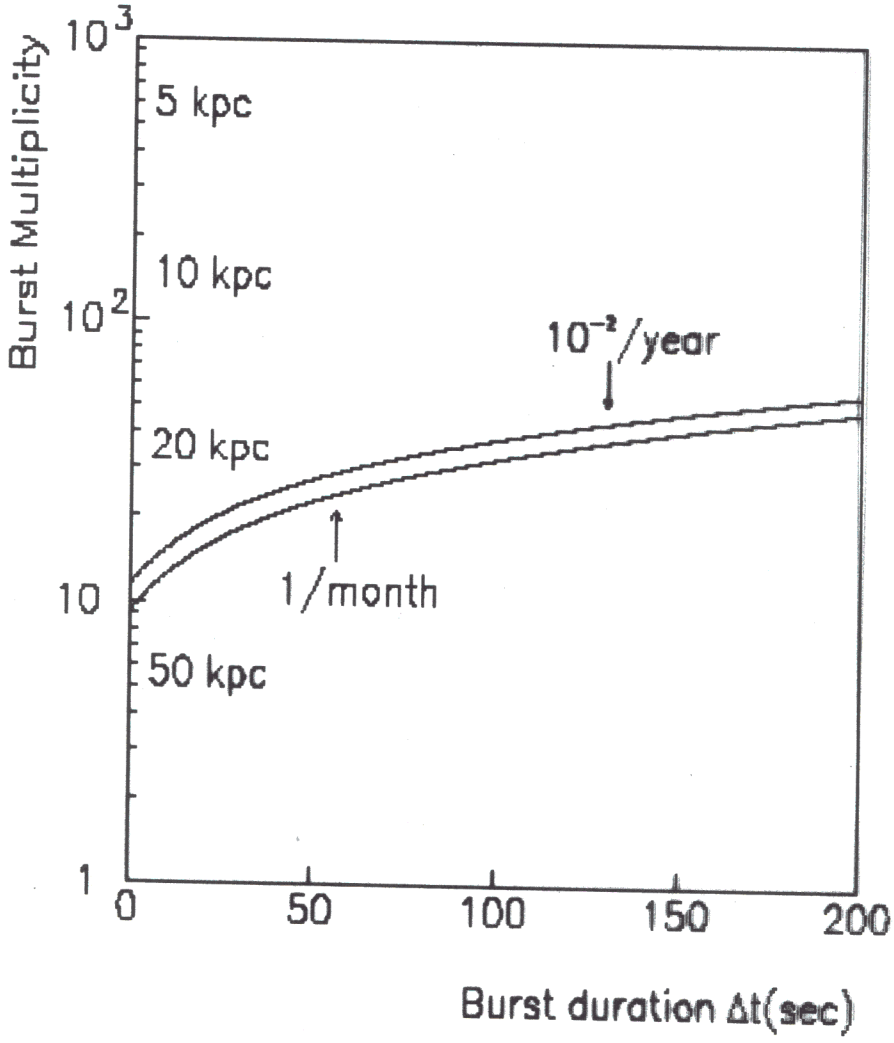
- At supernova energies, ν_x is observed only via NC
  - NC interactions can not be used to measure neutrino energy

LVD—1st dedicated SN Neutrino Observatory

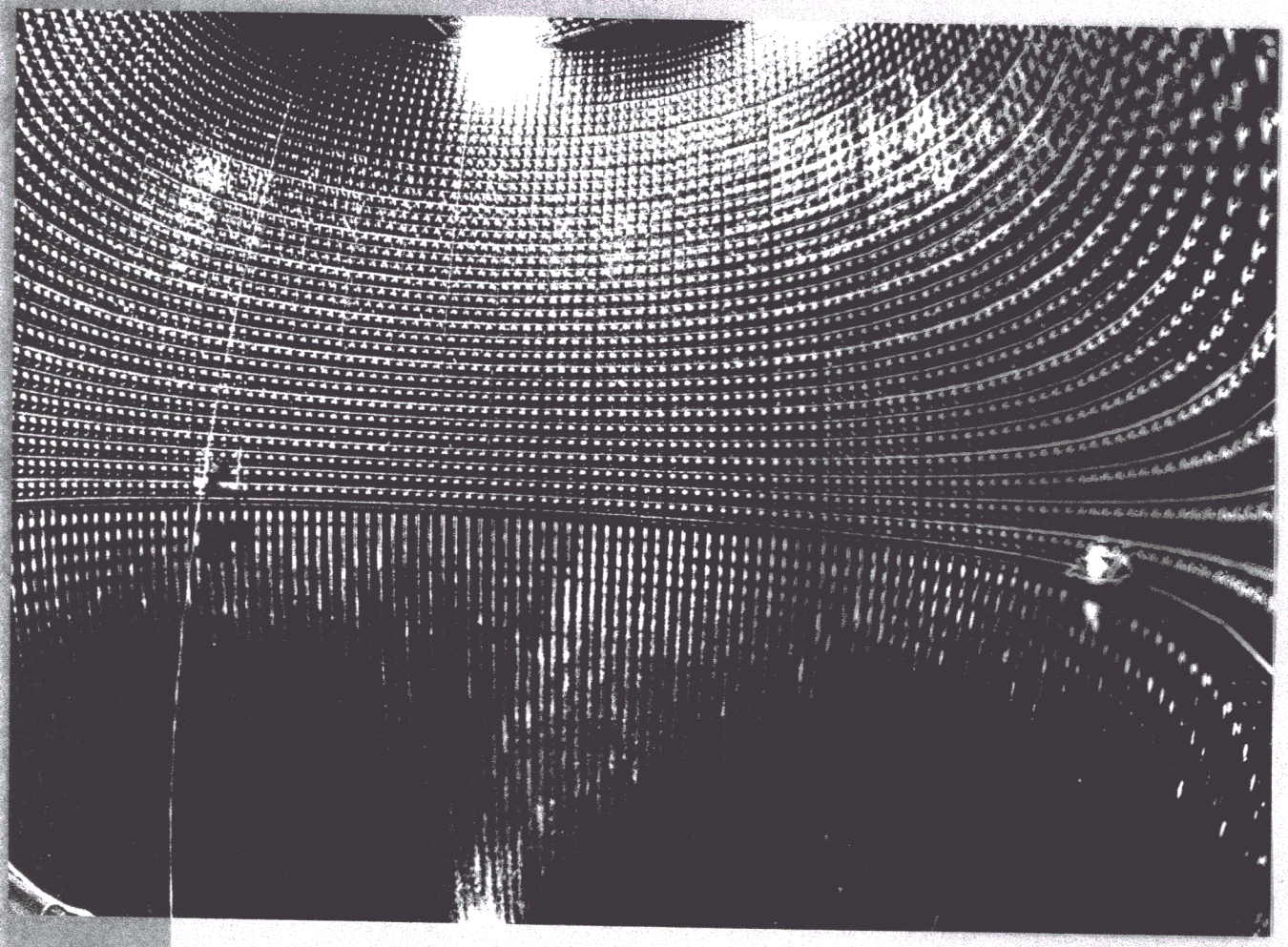
- Approx. 1000 ton of liquid scintillator at LNGS
  - Primarily sensitive to electron anti-neutrinos
    - **Essentially no identification of event type**



LVD Sensitivity



Super-Kamiokande is a 50,000 ton water Cherenkov detector at a depth of 1000 meters in the Kamioka Mozumi mine in Japan.



★ Super-K detects neutrinos from:

SuperKamiokande

✱ Signals

~ 300 ev / kt / $\left(\frac{R}{10\,kpc}\right)^2$

$\bar{\nu}_e\ p \rightarrow e^+ + n$ $\sim 6{,}000$

ν energy

$\nu_x\ e \rightarrow \nu_x\ e$ ~ 200

SN direction $\delta\theta \simeq \frac{10^\circ - 20^\circ}{\sqrt{N}}$

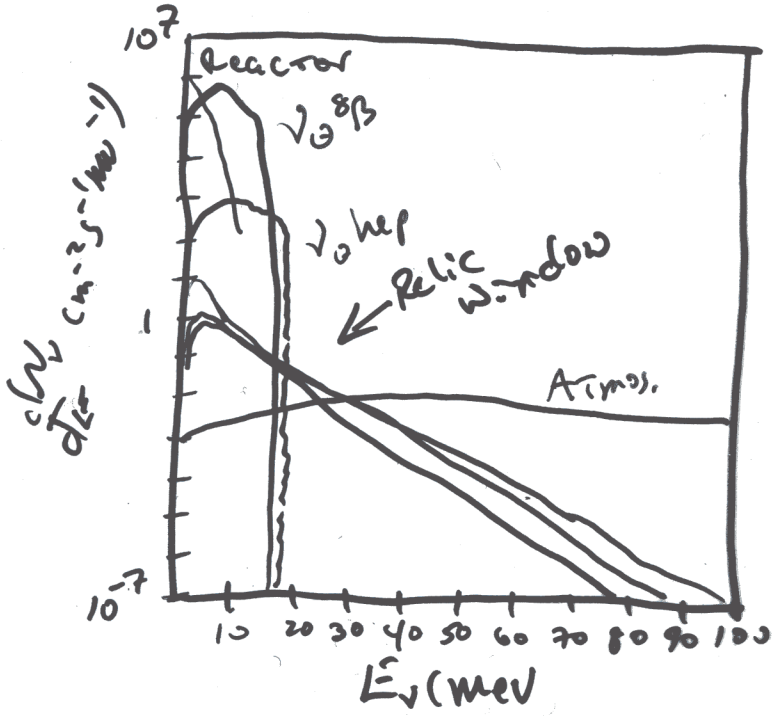
$\nu_x\ {}^{16}O \rightarrow \nu_x\ \gamma\ X$ ~ 700 ev

NC rate strong fcn. of

T_{ν_x}

Gd 'upgrade'

'Relic' SN $\bar{\nu}_e$'s



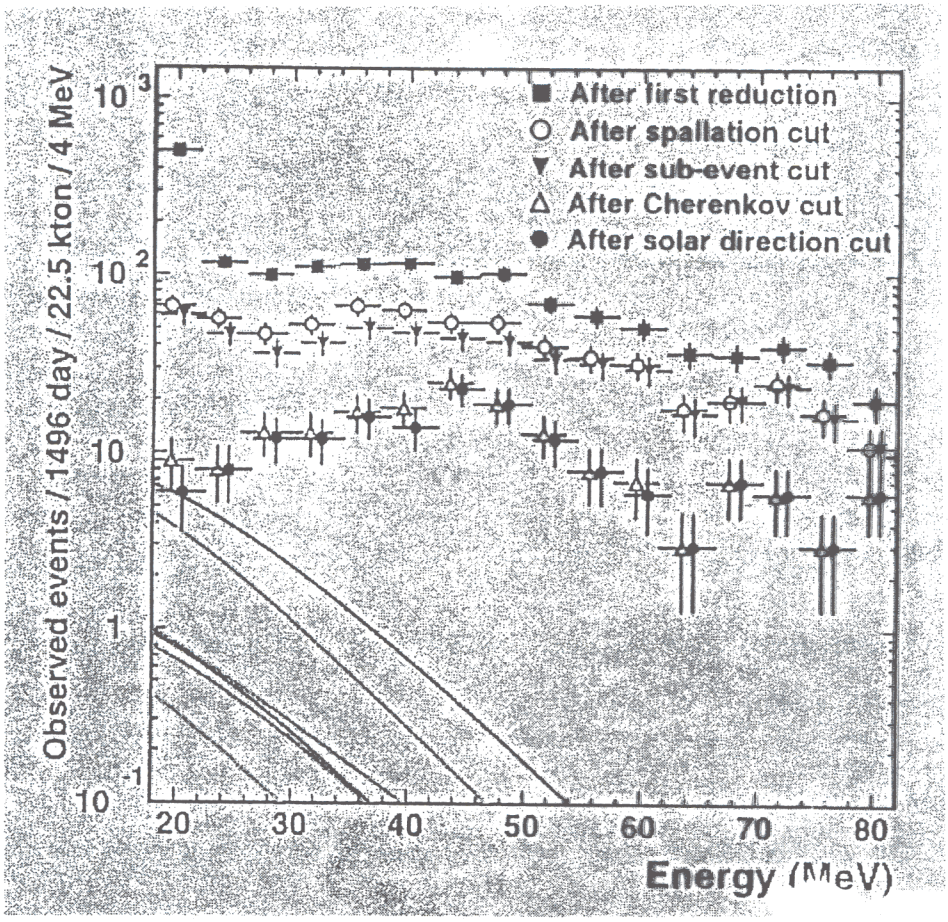
SK results

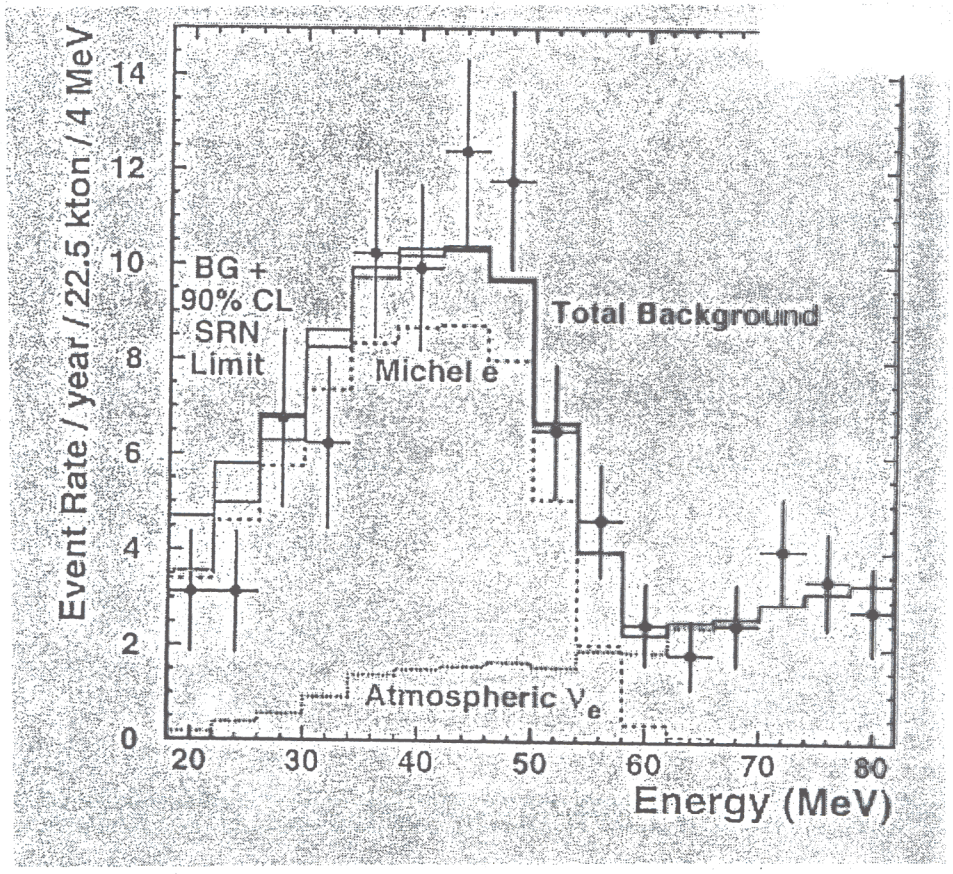
Spectra are model dep. ∴ results are model dep.

e.g.	SK	model
chem. evol. Hartmann + Woosley Astroport. Z., '97	$< 25\ \sqrt{E}\ \mathrm{cm^{-2}s^{-1}}$	8.3
constant SN rate Totani, Sato + Yoshii APS 460 '96	< 20	52

Fukugita + Kawasaki, MNRAS (astro-ph/0204376)

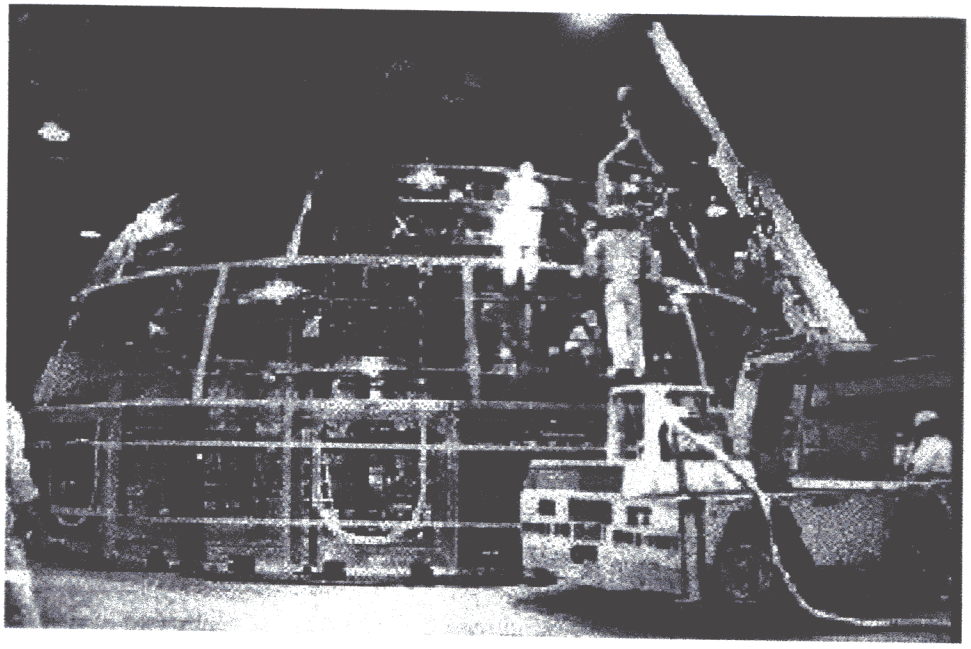
SFR $< 0.04 M_\odot\ \mathrm{yr^{-1}Mpc^{-3}}$ comparable to limits from radio obs.


After first reduction
After spallation cut
After sub-event cut
After Cherenkov cut
After solar direction cut
Observed events / 1496 day / 22.5 kton / 4 MeV
Energy (MeV)


BG + 90% CL SRN Limit
Total Background
Michel e
Atmospheric ν_e
Event Rate / year / 22.5 kton / 4 MeV
Energy (MeV)

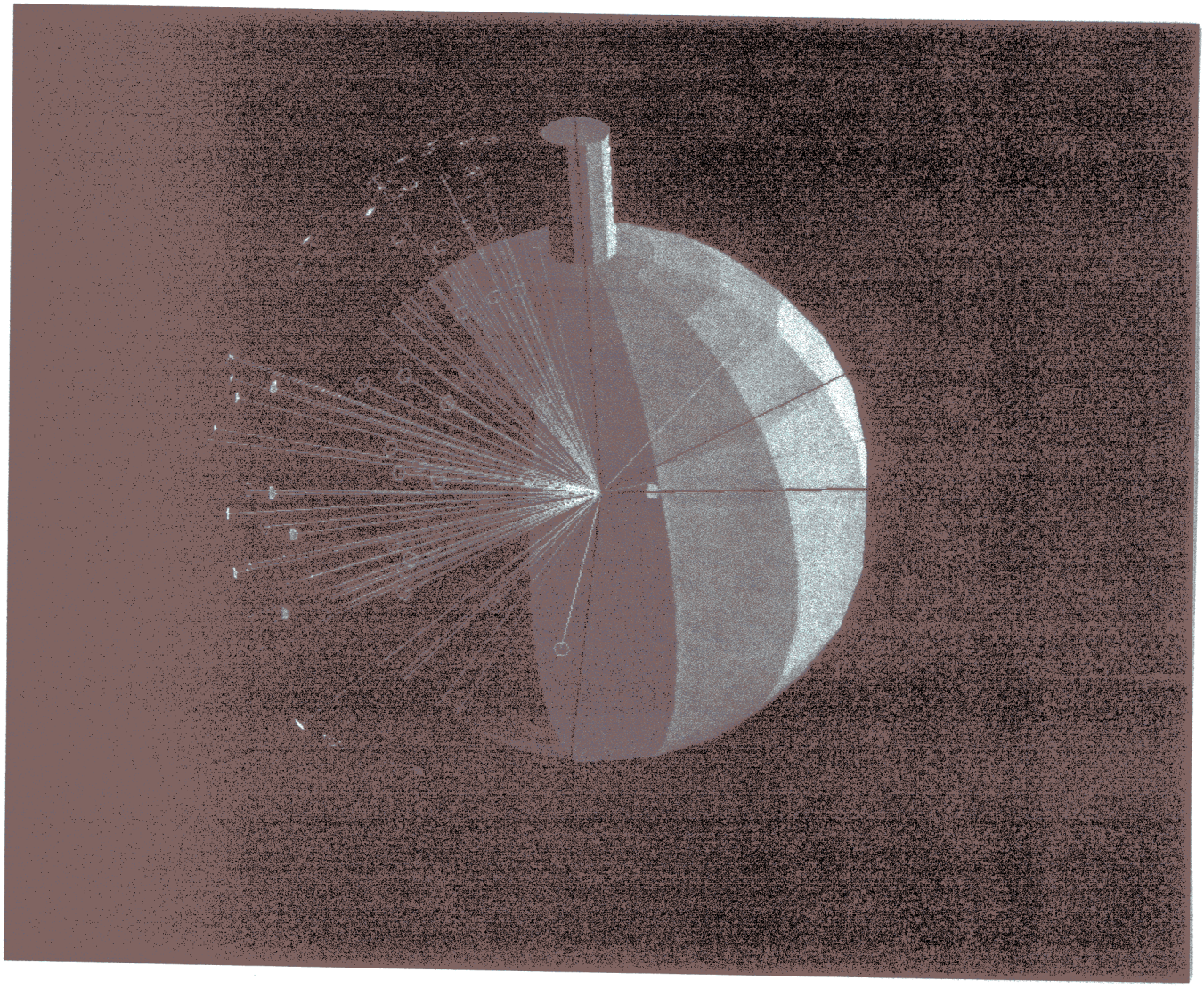
Another Solar (Supernova) Neutrino Detector--SNO

Located in Sudbury, Canada



uses 1,000 tons of D2O & 10,000 PMTs

SNO Works!!!



Breakdown of the Supernova Monte Carlo Results at 10 kpc, for the "Salt" Running Phase

In 1k tonne of heavy water

Reaction	#Events	Energy	Time	Pointing
CC: $\nu_e + d \rightarrow p + p + e^-$	72	y	y	*
CC: $\overline{\nu}_e + d \rightarrow n + n + e^+$	138	y	y	*
NC: $\nu_e + d \rightarrow \nu_e + p + n$	30	n	~y	n
NC: $\overline{\nu}_e + d \rightarrow \overline{\nu}_e + p + n$	32	n	~y	n
NC: $\nu_{\mu,\tau} + d \rightarrow \nu_{\mu,\tau} + p + n$	164	n	~y	n
ES: $\nu_e + e^- \rightarrow \nu_e + e^-$	8	~	y	y
ES: $\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^-$	3	~	y	y
ES: $\nu_{\mu,\tau} + e^- \rightarrow \nu_{\mu,\tau} + e^-$	4	~	y	y

In 1.4k tonnes of light water

Reaction	#Events	Energy	Time	Pointing
CC: $\overline{\nu}_e + p \rightarrow n + e^+$	331	y	y	*
ES: $\nu_e + e^- \rightarrow \nu_e + e^-$	12	~	y	y
ES: $\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^-$	5	~	y	y
ES: $\nu_{\mu,\tau} + e^- \rightarrow \nu_{\mu,\tau} + e^-$	5	~	y	y

Note: $\nu_{\mu,\tau}$ = "ν_μ" $= \nu_\mu + \overline{\nu}_\mu + \nu_\tau + \overline{\nu}_\tau$ and the significance of * and ~ is discussed in the text.

Non-supernova physics

- Direct neutrino mass measurement via T-O-F

$$\Delta t = 0.05(R/10\ \text{kpc})(m_\nu/1\ \text{eV})^2(1\ \text{MeV}/E_\nu)^2$$

  - ∴observation of a ~10 ms delayed burst would allow ~10 eV mass sensitivity
- Signature of 'invisible' nucleon decay in ^{208}Pb in LPC:

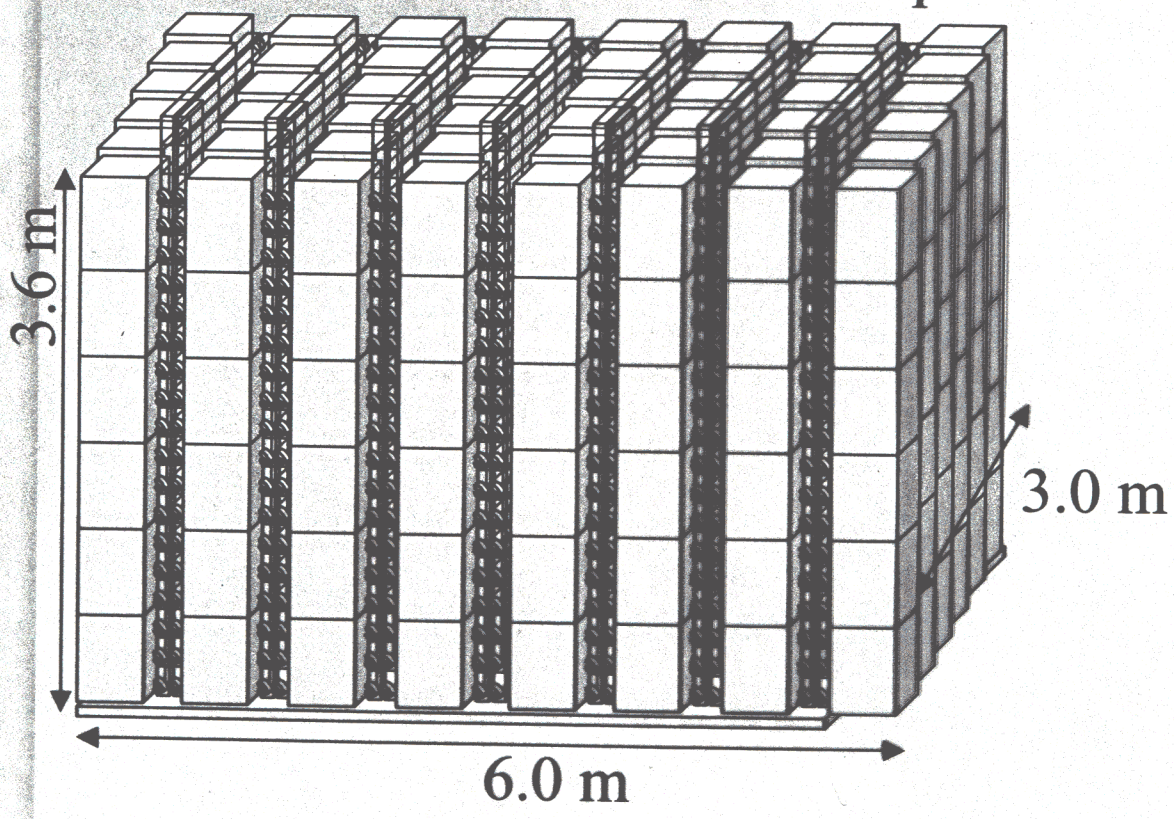
$$^{208}\text{Pb} \rightarrow {}^{207}\text{Pb}^* + 3\nu \rightarrow {}^{206}\text{Pb}^* + n$$
$$\rightarrow {}^{205}\text{Pb}^* + n\ (+\ n)$$
$$\rightarrow {}^{205}\text{Pb} + \gamma + 2n$$

  - **Studies indicate ~1,000 improvement in τ/B**
- Observation of very small θ_{13}
  - Signature of '0' is 'warm' ν_e spectrum
  - Preliminary study suggests $\theta_{13} > 10^{-4}$ observable
  - Detailed calculations underway

Lead-slab Portion of OMNIS--II

Schematic ½ kT lead module for **OMNIS**

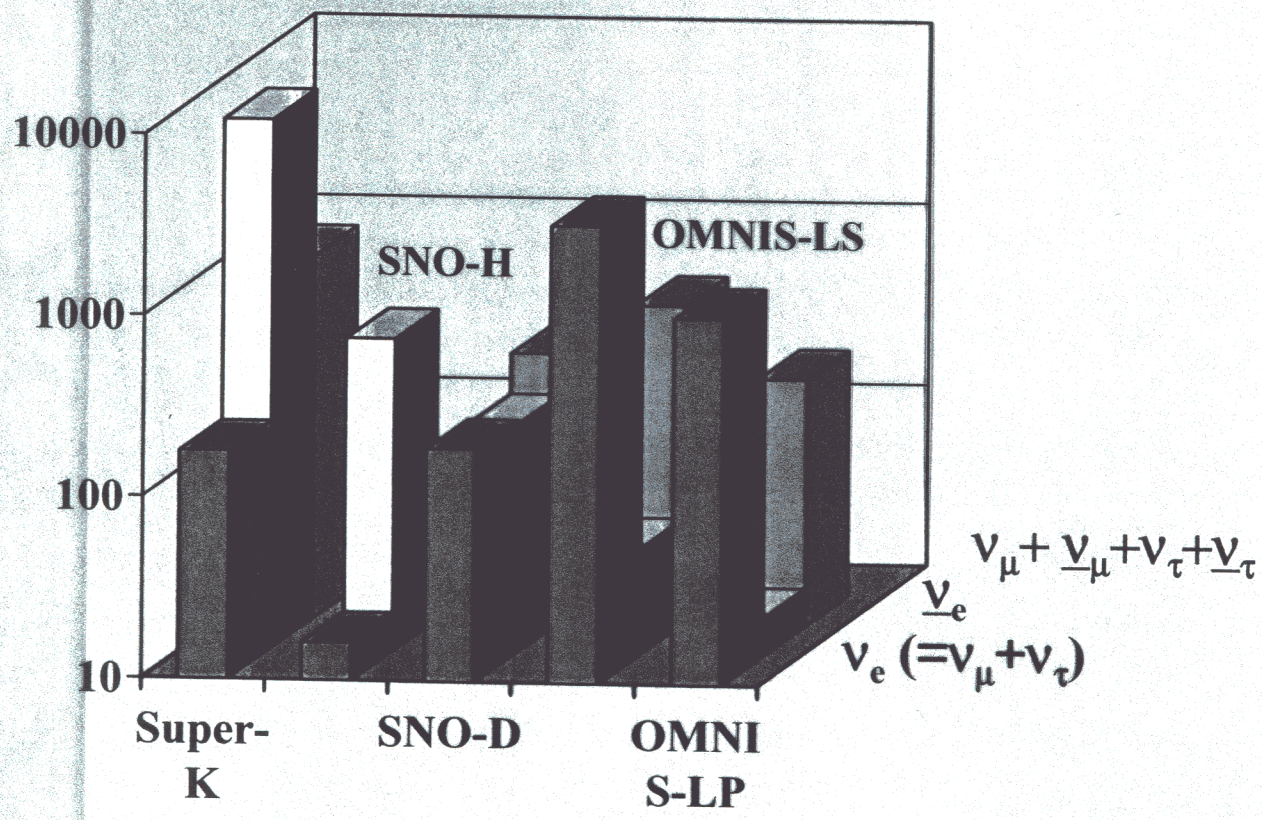
2 kT total, ~2,000 events from supernova



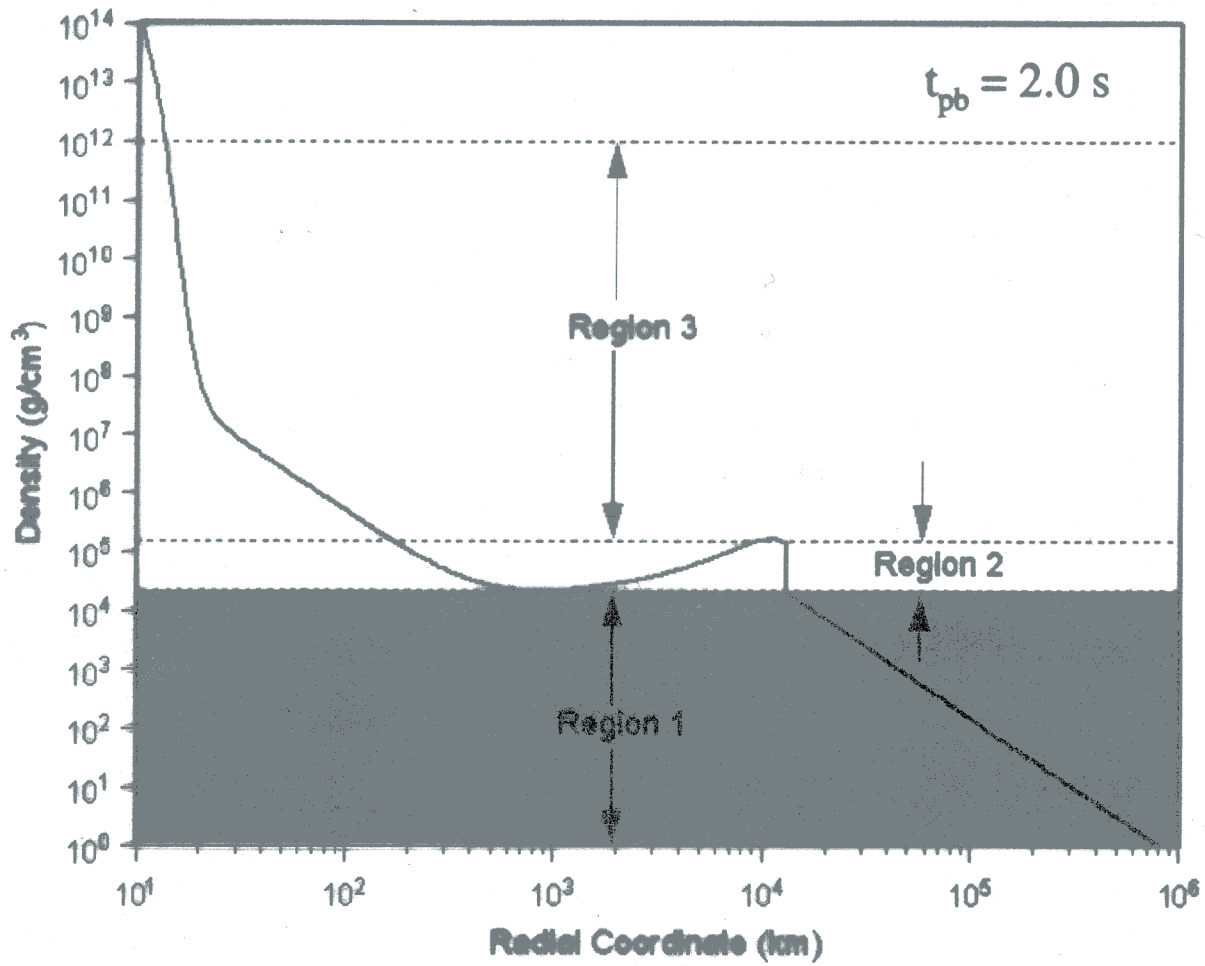
NB. Top & front lead wall not shown for clarity

OMNIS Complementarities

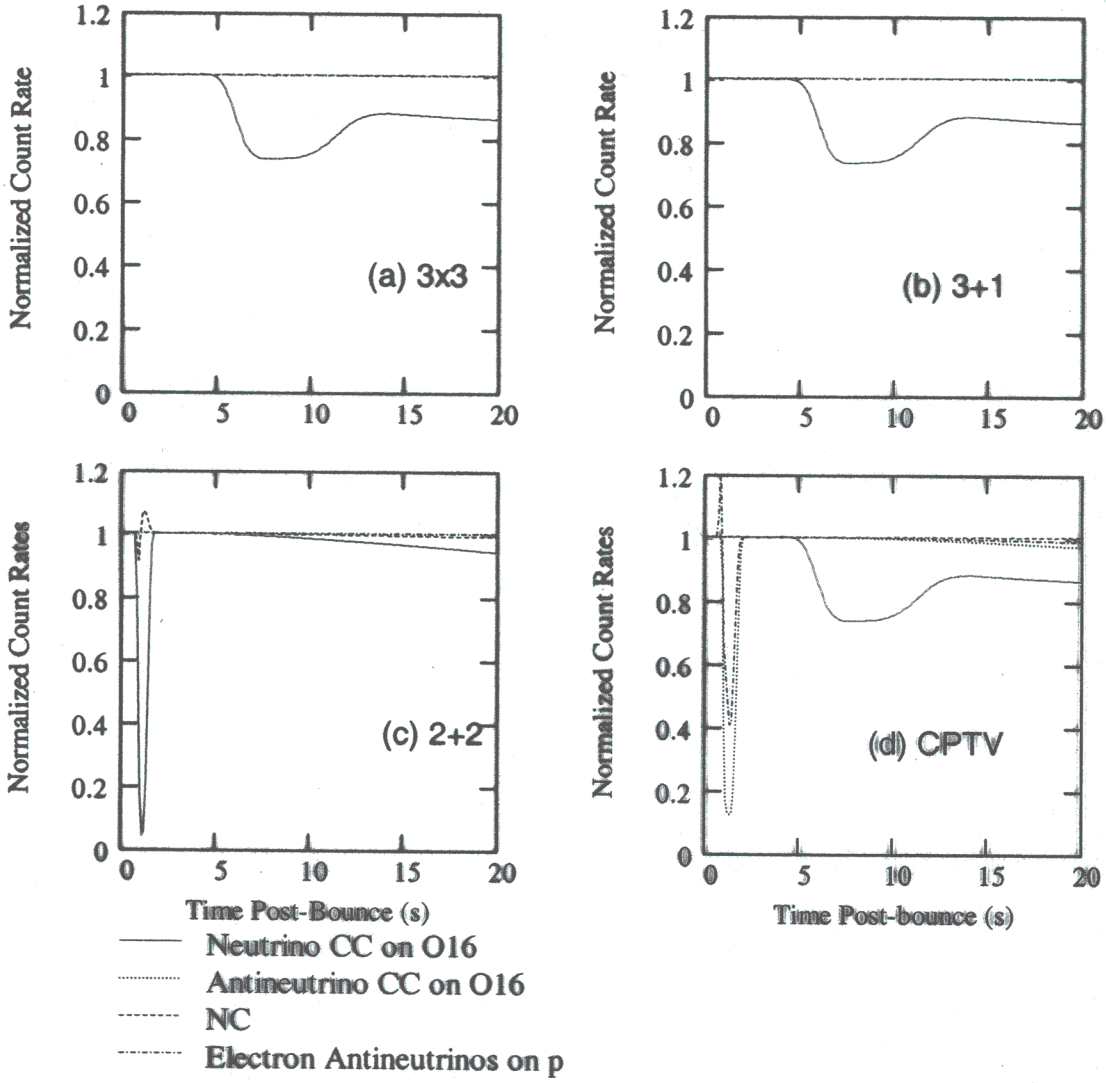
★ Event yields for SN at 8 kpc



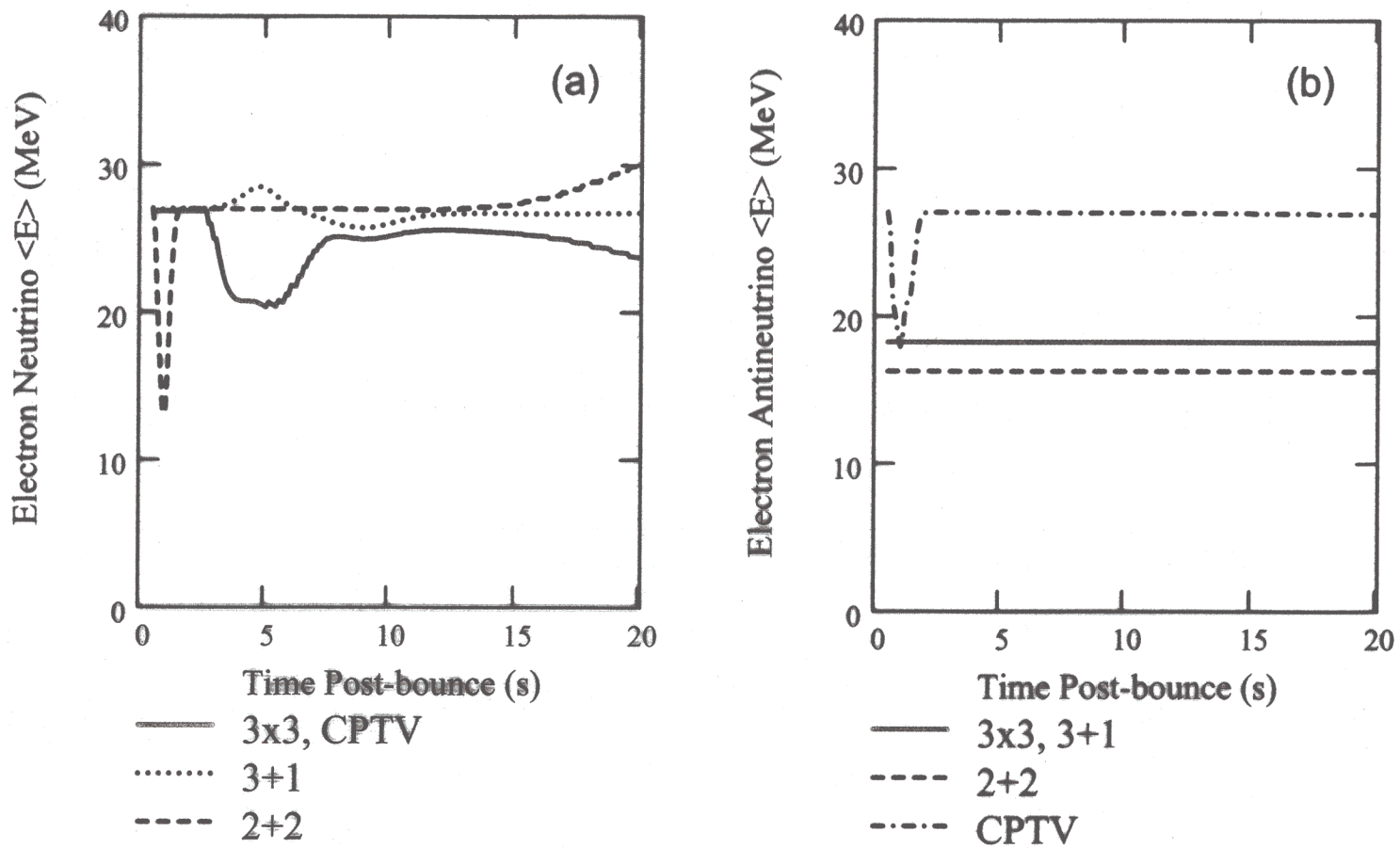
Supernova Density Profile Calculation Regions

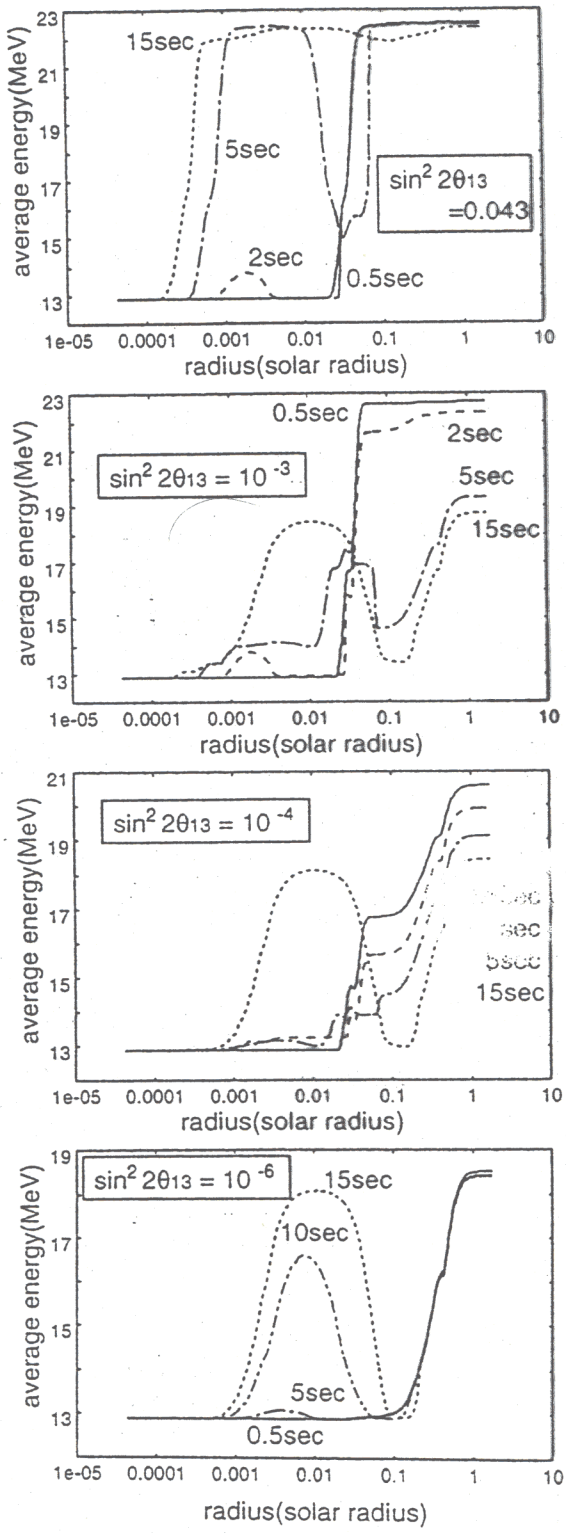


SNII Neutrino Burst Normalized Signals (S-K)



Average Electron Neutrino Energy as a Function of Time




average energy(MeV)
radius(solar radius)
15sec
5sec
2sec
0.5sec
sin² 2θ13 =0.043
sin² 2θ13 = 10 -3
sin² 2θ13 = 10 -4
sin² 2θ13 = 10 -6
10sec

Summary

- Why Supernova?
  - Nearly every field of physics comes into play in SN explosion
    - Stat. mech., (magneto-)hydro., nuclear, particle, gen. rel.
  - Thought to drive many very important processes in the cosmos
    - SN explosion, nucleosynthesis, CR acceleration, Gamma-ray bursts? Black Hole formation?
- Why Neutrinos?
  - Dominate energy loss of any hot, dense region
    - Our only messengers into the interior
    - Thought to drive the shock & explosion
    - Thought to drive nucleosynthesis
    - Thought to drive GRB mechanism
  - Clearly there is a close interplay btw. neutrino properties/oscillations and astrophysical mechanisms