NEUTRINO MIXING AND THE SUPERNOVA NEUTRINO SIGNAL

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- *Introduction, motivation*
- *generalities*
- *methods & physics potential (future, past)*
- *perspectives and conclusions*

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Today we know that neutrinos are massive and have mixing.

The following quantities have been measured:

$|\Delta m^2_{32}| \simeq |\Delta m^2_{31}|$, θ_{23} (atmospheric neutrinos)

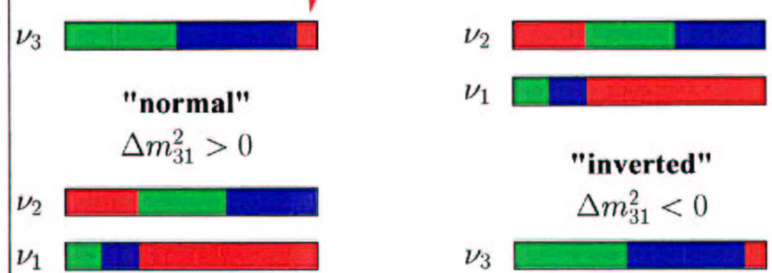
Δm^2_{21}, θ_{12} (SNO, KamLand)

What are the next goals?

1) non−oscillation: mass, magnetic moment, Dirac/Majorana....

2) Oscillation : 13-mixing angle, θ_{13} , ~~CP~~

mass hierarchy :



Why study oscillations with supernova neutrinos?

Different setup → *Different possibilities...*

all flavors, neutrinos and antineutrinos

$E \sim 10 - 80$ MeV (larger than solar ν)

larger regeneration effects in the Earth for LMA parameters

Very long base-line: $D \sim 10$ kpc (galactic SN)

time-delay tests (neutrino mass)

short duration: $\Delta t \sim 10$ s

very dense medium:

$\rho_{star} \sim 1 - 10^{10}\ \mathrm{g \cdot cm^{-3}}$

$\gg \rho_{sun}$

$\rho_{res} = \frac{|\Delta m^2_{13}| m_N}{\sqrt{2} G_F E}$

$\sim 10^3\ \mathrm{g \cdot cm^{-3}}$

($E \sim 10$ MeV)

θ_{13} is resonantly amplified (MSW)

large conversion effects!

($1\,\mathrm{pc} \simeq 3 \cdot 10^{16}\,\mathrm{m}$)

.... and different problems :

we still do not have a "Standard Supernova Model"

The physics of neutrino transport in the star is the subject of active research

Due to the interplay of many different physical effects, the problem is complicated, and we have large uncertainties on:

- *Energy spectra:*
  Fermi−Dirac? "pinched"?
- *Difference of fluxes/spectra in the different flavors:*
  hierarchy of energies?
  similar luminosities?
- *time evolution of the neutrino fluxes*
- *density profile of the star:*
  power law? changes with time?

See e.g. Keil, Raffelt and Janka, astro-ph/020835

neutrino energy spectra and luminosities: a naive argument..

- **emission from a thermal sphere (neutrinosphere):**

  $\longrightarrow$ **thermal spectra**

- **different flavors have different interactions with the medium:** $\longrightarrow$ **"hierarchy" of the spectra**

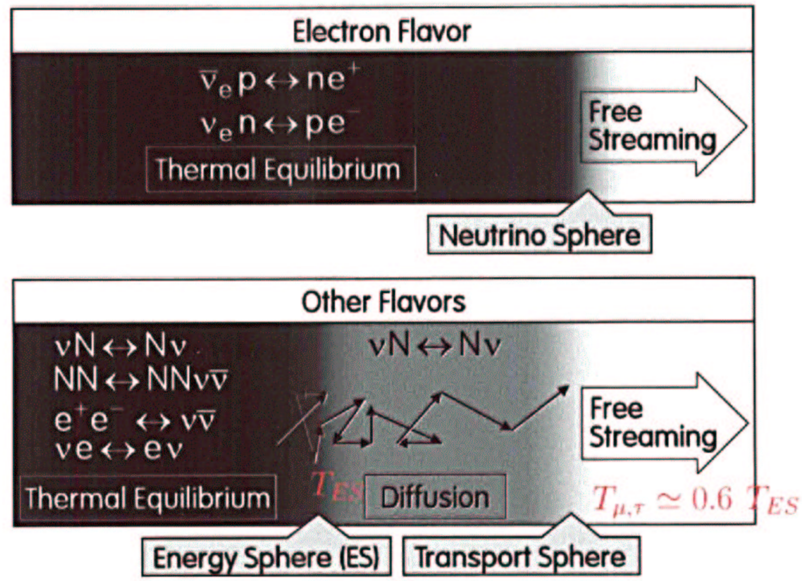
$$\begin{array}{ccccc} \nu_e + n & & \bar{\nu}_e + p & & \text{NC only} \\ \langle E_e \rangle & < & \langle E_{\bar{e}} \rangle & < & \langle E_{\mu,\tau,\bar{\mu},\bar{\tau}} \rangle \\ \sim 9-11 \text{ MeV} & & \sim 14-17 \text{ MeV} & & \sim 21-24 \text{ MeV} \end{array}$$

- **"equipartition" of luminosities between flavors:**

$$L_e \simeq L_{\bar{e}} \simeq L_{\mu,\tau,\bar{\mu},\bar{\tau}}$$

however, physics is more complicated...

the non−electron energy sphere is more internal, but diffusion must be taken into account....



effective **thermal spectra, smaller differences in energies:**

$$\langle E_e \rangle < \langle E_{\bar{e}} \rangle < \langle E_{\mu,\tau} \rangle$$
$$0.8 \ : \ 1 \ : \ 1.1$$

Similar luminosities (~ factor of 2)

[G.Raffelt, astro−ph/0105250]

The particle– and astro–physical aspects of the phenomenon are tightly connected.

1. to probe θ_{13} and the mass hierarchy

   large astrophysical uncertainties must be taken into account.

2. to probe astrophysical parameters,

   θ_{13} and the hierarchy must be known (terrestrial experiments)

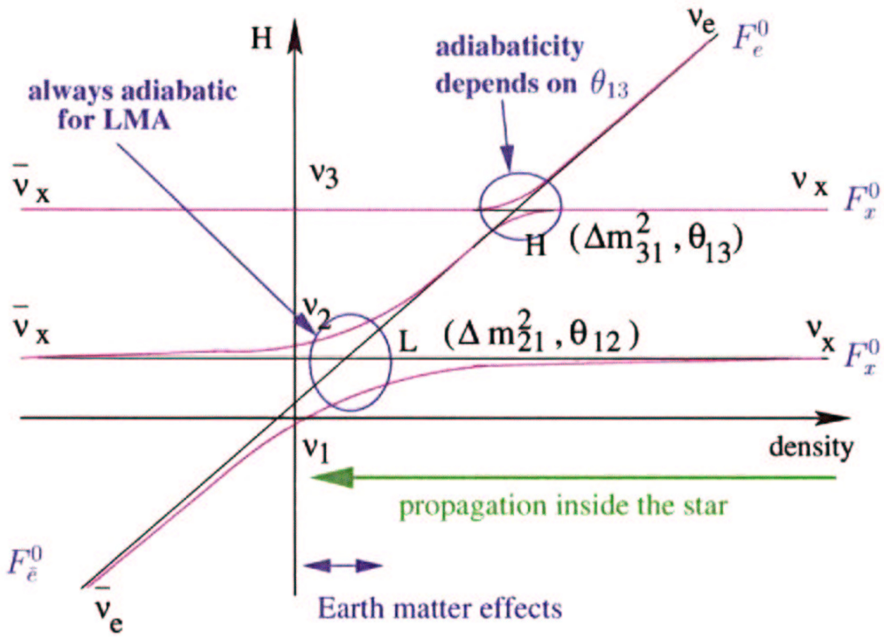
5

life of supernova neutrinos:

conversion effects

conversion effects: swap of fluxes

for normal hierarchy:



Permutation: (LMA parameters taken)

P_H jump probability

$$F_e = P_H P_{2e} F_e^0 + (1 - P_H P_{2e}) F_x^0 \qquad P_{2e} \equiv P(\nu_2 \to \nu_e)$$

$$F_{\bar{e}} = P_{1\bar{e}} F_{\bar{e}}^0 + (1 - P_{1\bar{e}}) F_{\bar{x}}^0$$

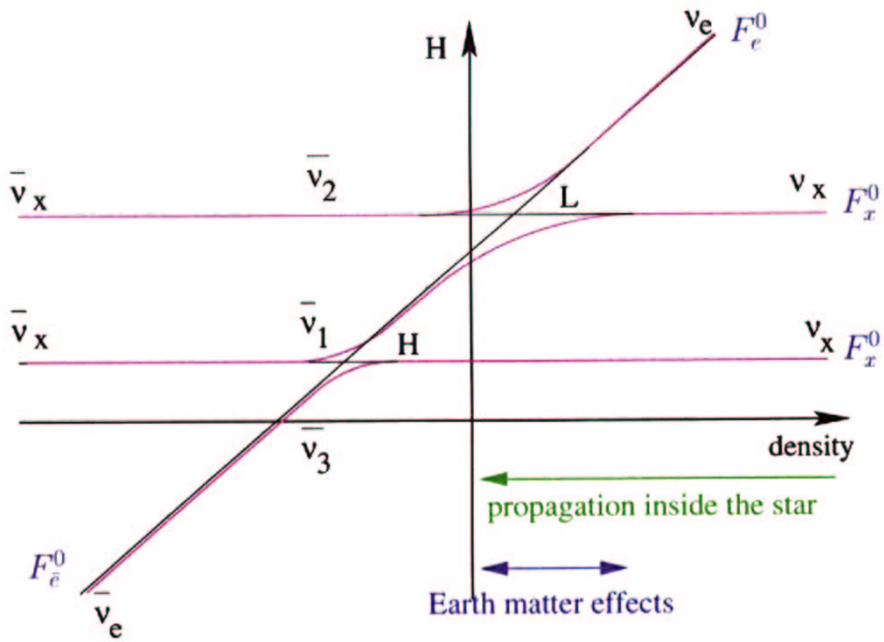
hardening of spectra

with no Earth crossing:

$$P_{2e} = \sin^2\theta_{12} \qquad P_{1\bar{e}} = \cos^2\theta_{12}$$

5

for inverted hierarchy:



$$F_e = P_{2e} F_e^0 + (1 - P_{2e}) F_x^0$$

$$F_{\bar{e}} = P_H P_{1\bar{e}} F_{\bar{e}}^0 + (1 - P_H P_{1\bar{e}}) F_{\bar{x}}^0$$

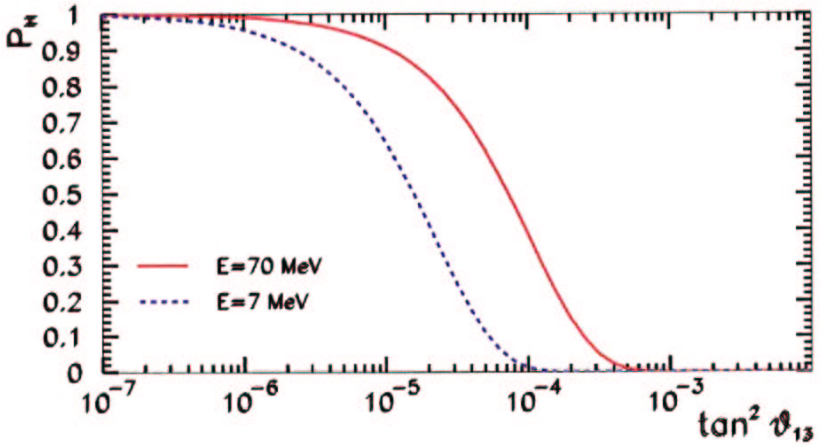
6

Jump probability and θ_{13}

taking the density profile of the progenitor star, $\rho(r) \propto r^{-3}$, the jump probability in the high density resonance has the form:

$$P_H \propto exp\left[-\sin^2\theta_{13}\left(\frac{|\Delta m^2_{31}|}{E}\right)^{2/3} const\right]$$

(Δm^2_{31} atmospheric mass splitting)



Probing oscillation parameters:

observed fluxes: (F^0_α original fluxes)

ν_e: $F_e = pF^0_e + (1-p)F^0_x$

$\bar\nu_e$: $F_{\bar e} = \bar pF^0_{\bar e} + (1-\bar p)F^0_{\bar x}$

No conversion effects if $F^0_e = F^0_x,\ F^0_{\bar e} = F^0_{\bar x}$ *!*

different energy spectra for electron and non−electron flavors is a necessary condition!

The future:

What can we learn from a galactic supernova ?

Detection of supernova neutrinos:

what is needed? high statistics, energy resolution, timing, flavor sensitivity, $\nu - \bar{\nu}$ sensitivity, directionality, low energy threshold....

what is feasible? examples...

WATER: SUPERKAMIOKANDE [Japan, 32kt volume] (UNO, HyperK..)

$\bar{\nu}_e \; p \to e^+ \; n$	~8000 events (D=10kpc)
$\nu_{e,\mu,\tau} \; e^- \to \nu_{e,\mu,\tau} \; e^-$ (ES)	~200+60+60 events
$\bar{\nu}_e \; O \to N \; e^+$	
$\nu_e \; O \to F \; e^-$	

HEAVY WATER: SNO [Sudbury, Ontario, 1kt volume]

$\nu_e \; d \to p \; p \; e^-$	~240 events
$\bar{\nu}_e \; d \to n \; n \; e^+$	~120 events
$\nu_{e,\nu,\tau} \; d \to p \; n \; \nu_{e,\mu,\tau}$	~490 events

SCINTILLATOR: KamLAND [Japan, 1kt] (Borexino, LVD...)

$\bar{\nu}_e \; p \to e^+ \; n$	~330 events
$\nu \; p \to \nu \; p$	~300 events above 150 keV
$\nu_e \; {}^{12}C \to {}^{12} N \; e^-$	

How to extract θ_{13} and the hierarchy ?

you have to deal with many (14 !) parameters:

$$\langle E_e\rangle,\ \langle E_{\bar{e}}\rangle,\ \langle E_x\rangle,\ \langle E_{\bar{x}}\rangle \quad L_e,\ L_{\bar{e}},\ L_x,$$

$$\eta_e,\ \eta_{\bar{e}},\ \eta_x,\ \rho_0 \quad ,n\ |\Delta m^2_{31}| \quad ,\theta_{12}$$

1. Global (astro+particle) fit:

V.Barger, D.Marfatia and B.P.Wood, Phys. Lett.B 547:37−42,2002

H.Minakata et al., Phys.Lett.B 542:239−244,2002

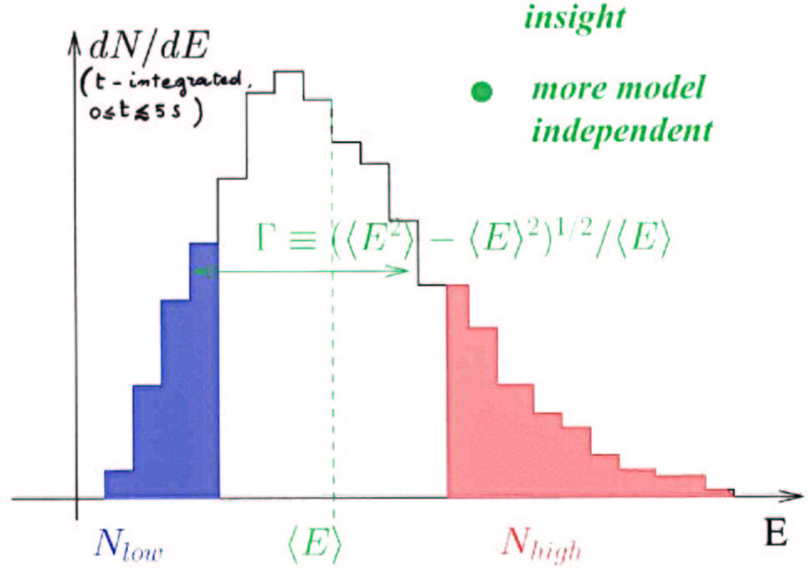
- **extensive;**
- **needs reduction of number of variables**

2. Identify and study (analytically!) observables sensitive to θ_{13} and to the mass hierarchy:

C.Lunardini & A.Yu.Smirnov, hep−ph/0302033

see also: Takahashi & Sato, Phys. Rev. D64:093004,2001

- *Focused, physical insight*
- *more model independent*



$$R_{low} \equiv \frac{N_{low}(\nu_e)}{N_{low}(\bar{\nu}_e)} \qquad R_{high} \equiv \frac{N_{high}(\nu_e)}{N_{high}(\bar{\nu}_e)}$$

$$r_\Gamma \equiv \frac{\Gamma(\nu_e)}{\Gamma(\bar{\nu}_e)} \qquad r_E \equiv \frac{\langle E\rangle_{\nu_e}}{\langle E\rangle_{\bar{\nu}_e}}$$

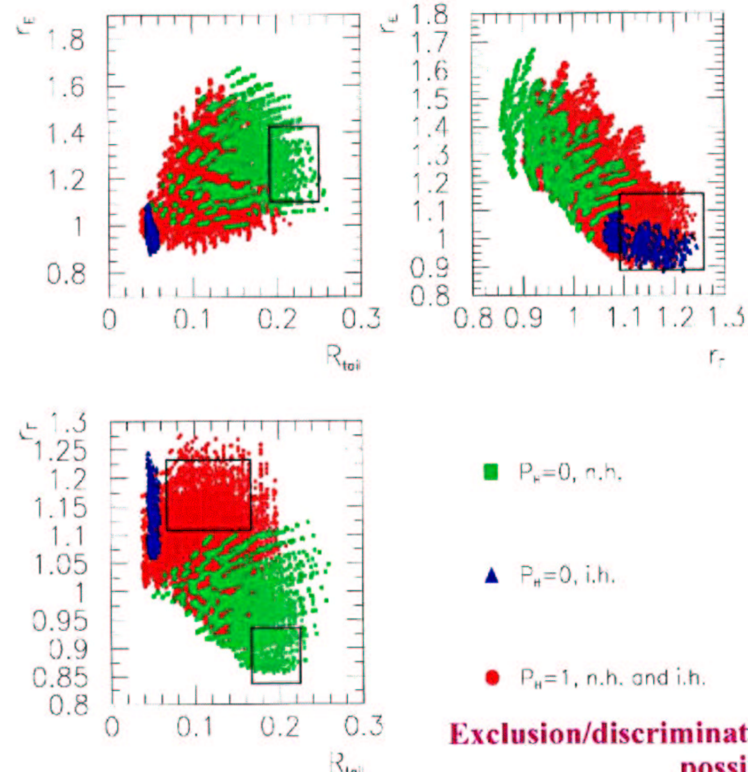
distinguishing between extreme possibilities:

		permutation	r_Γ	r_E
A ■	$P_H = 0$ $(s^2_{13} > 10^{-4})$ n.h.	ν_e: **complete** / $\bar\nu_e$: **weak** $(\propto \sin^2\theta_{12})$	< 1	> 1
B ▲	$P_H = 0$ $(s^2_{13} > 10^{-4})$ i.h.	ν_e: **strong** $(\propto \cos^2\theta_{12})$ / $\bar\nu_e$: **complete**	> 1	< 1
C ●	$P_H = 1$ $(s^2_{13} < 5\ 10^{-5})$ both n.h. and i.h.	ν_e: **strong** $(\propto \cos^2\theta_{12})$ / $\bar\nu_e$: **weak** $(\propto \sin^2\theta_{12})$	**intermediate**	**intermediate**

9

scatter plots : $\nu_e + d$ CC at SNO

$\bar\nu_e + p$ CC at SuperKamiokande



Exclusion/discrimination possible

Parameters:

$T_{\bar\nu_e} = 4 - 7$ MeV. $T_{\nu_x}/T_{\bar\nu_e} = 1.1 - 1.6$ $\quad T_{\nu_e}/T_{\bar\nu_e} = 0.5 - 0.8$

$L_{\nu_e}/L_{\nu_x} = 0.5 - 2$. $L_{\bar\nu_e}/L_{\bar\nu_x} = 0.5 - 2$. $\tan^2\theta_{12} = 0.34 - 0.42$.

$\eta_{\nu_e} = 0 - 3$. $\eta_{\bar\nu_e} = 0 - 3$. $\eta_{\nu_x} = 0 - 2$ $\quad L_{\nu_x} \simeq L_{\bar\nu_x}$

$T_{\bar\nu_x} - T_{\nu_x} = 0.3 - 0.5$ MeV $\quad |\Delta m^2_{31}| = 3 \cdot 10^{-3}\ \mathrm{eV}^2\ (1 \pm 0.2)$

cuts for R_{taie} : (OPTIMIZED) $E \geq 45$ MeV (ν_e)

$E \geq 55$ MeV $(\bar\nu_e)$

More on R_{high}:

High−energy cuts

$+$

$F^0_x \simeq F^0_{\bar{x}}$

$+$

$\sigma(\bar{\nu}_e + p) \propto \sigma(\nu_e + d) \propto E^2$

$+$

$\langle E_x \rangle > \langle E_{\bar{e}} \rangle, \langle E_e \rangle$

$=$

reduction of $\nu_e, \bar{\nu}_e$ contributions

$\downarrow$

analytical treatment (simplifications)

$+$

cancellations of uncertainties

$$R_{high} = Q\frac{1-\langle p \rangle + \alpha \langle p \rangle}{1-\langle \bar{p} \rangle + \bar{\alpha} \langle \bar{p} \rangle}$$

$\bar{p}$: $\bar{\nu}_e$ **survival probability**

p : ν_e **survival probability**

$Q = Q(thresholds, \cancel{F^0_x, F^0_{\bar{x}}})$ **precisely calculable** for suitable choice of energy cuts

$\alpha = \alpha(F^0_x, F^0_e)$

$\bar{\alpha} = \bar{\alpha}(F^0_{\bar{x}}, F^0_{\bar{e}})$

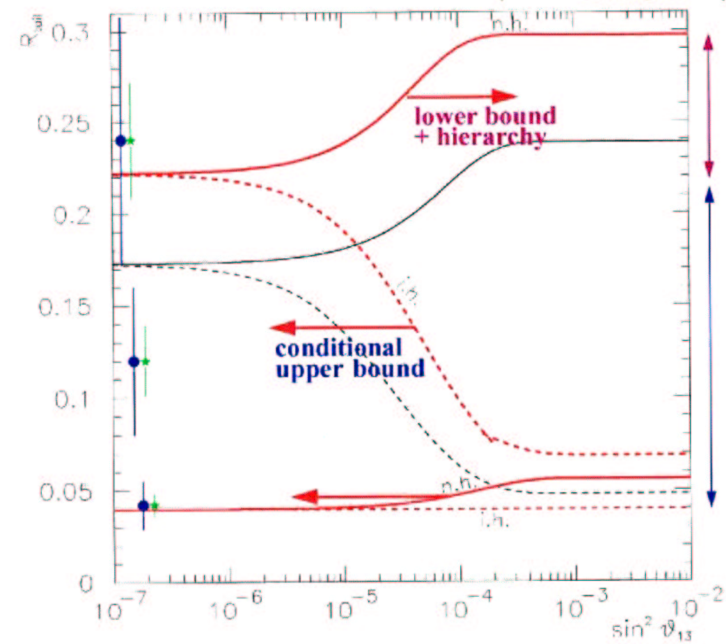
contribution of original $\nu_e, \bar{\nu}_e$ fluxes small if $T_e, T_{\bar{e}} \ll T_x$

Results :

(No Earth crossing)

cuts: $E \gtrsim 45$ MeV (ν_e)
$E \gtrsim 55$ MeV ($\bar{\nu}_e$)

$\left(\begin{array}{l} Q \simeq 0.063 \\ 0 \le \alpha \le 0.42 \\ 0 \le \bar{\alpha} \le 1 \end{array} \right)$



n.h. — n.h. "ideal"

i.h. — i.h. "ideal"

D=8.5 kpc

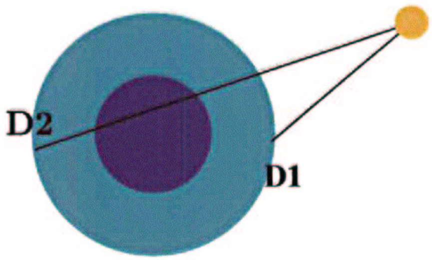
D=4 kpc

neglecting the contribution of original ν_e and $\bar{\nu}_e$ fluxes ($\alpha = \bar{\alpha} = 0$)

[Generalization to Earth crossing trajectories is possible with similar results]

other possibilities to probe θ_{13} and the mass hierarchy:

1. Earth matter effects: [Dighe & Smirnov, PRD62:033007,2000]



for n.h.:

$$F_e^{D2} - F_e^{D1} = P_H(\theta_{13}) f_{reg} \left(F_e^0 - F_x^0\right)$$

$$f_{reg} = f_{reg}(\theta_{12}, \Delta m^2_{21})$$

(for i.h.. similar results in $\bar{\nu}_e$ channel)

2. Shock–wave effects: [Schirato & Fuller, astro–ph/0205390]

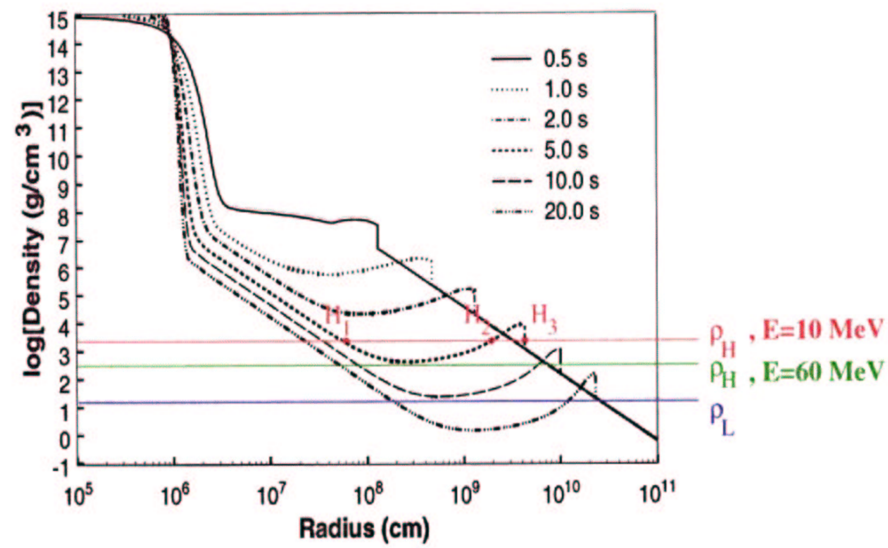
$P_H = P_H(t)$ **if** $\sin^2\theta_{13} > 10^{-3}$

- **Softening wave**
- **delayed Earth matter effects**

[Lunardini & Smirnov, hep–ph/0302033]

Shock–wave effects: how many resonances?

[R.C.Schirato & G.M.Fuller, astro–ph/0205390]



at late times (t=5 –10 s) the shock–wave reaches the density layers where flavor conversion occurs: multiple resonances take place

→ *significant impact on the conversion effects!*
interesting time structure of the signal!

(however effects are suppressed by luminosity decay)

18z

The past: back to SN1987A....

Now we know

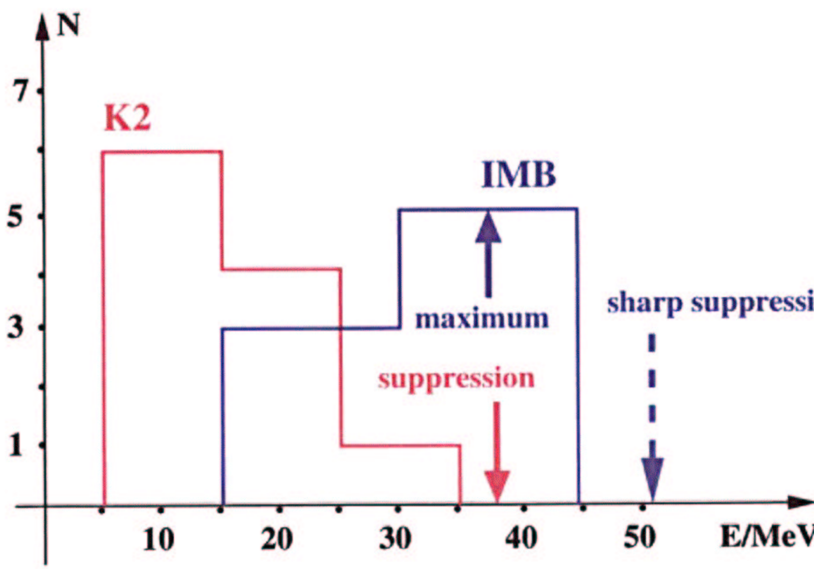
that conversion happened !

A look at the data: energy spectra

Kamiokande–2 (K2): water, 11 $\bar{\nu}_e$ events in ~ 13 sec

IMB : water, 8 $\bar{\nu}_e$ events in ~ 6 sec
(higher energy threshold)

[other (more controversial) signals: Baksan, Mont Blanc]



Though the general predictions are confirmed,

"strange" differences exist in the two spectra....

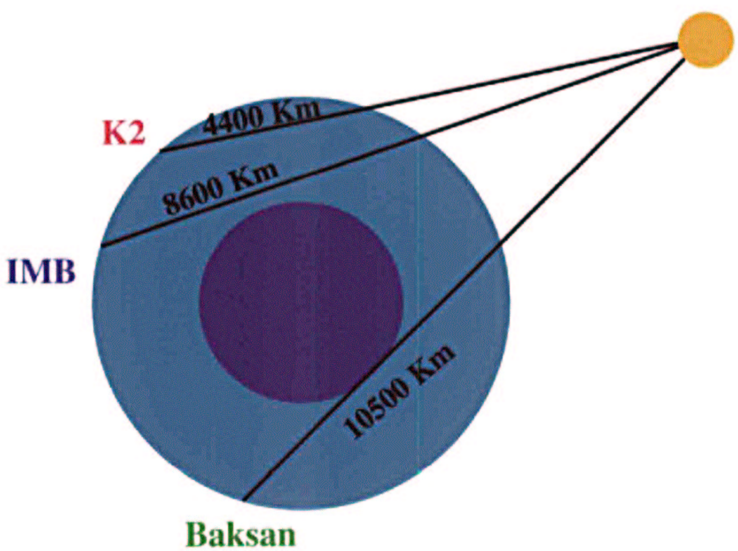
Interpretation of the data:

- flavor conversion effects must be included:

  Conversion in the star

  Regeneration of $\bar{\nu}_e$ inside the Earth (LMA-MSW)

- Differences between different experiments are expected: *different trajectories in the Earth* → *different phases of oscillations!*



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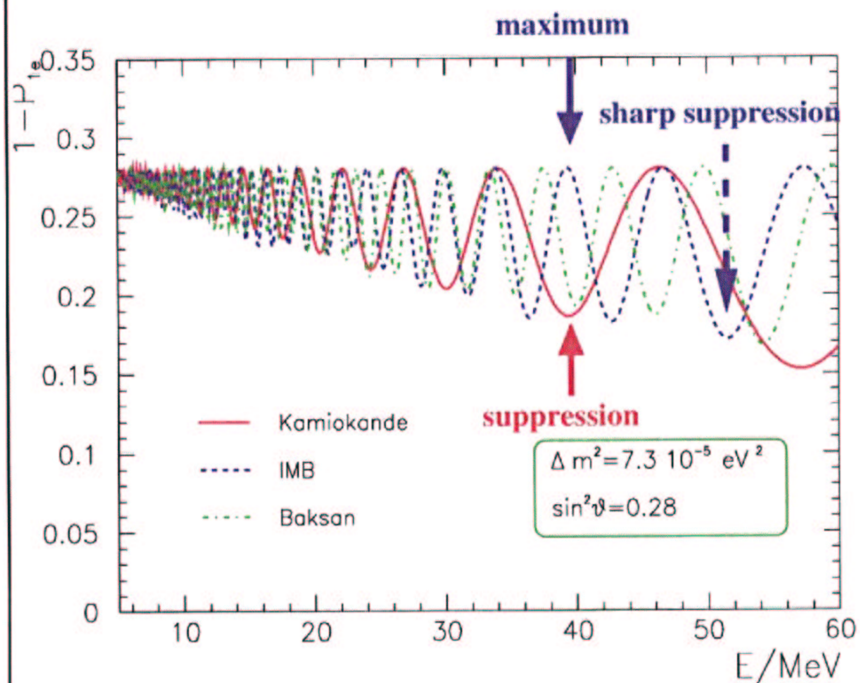
Conversion probabilities:

(for the Solar + KamLand best fit point)

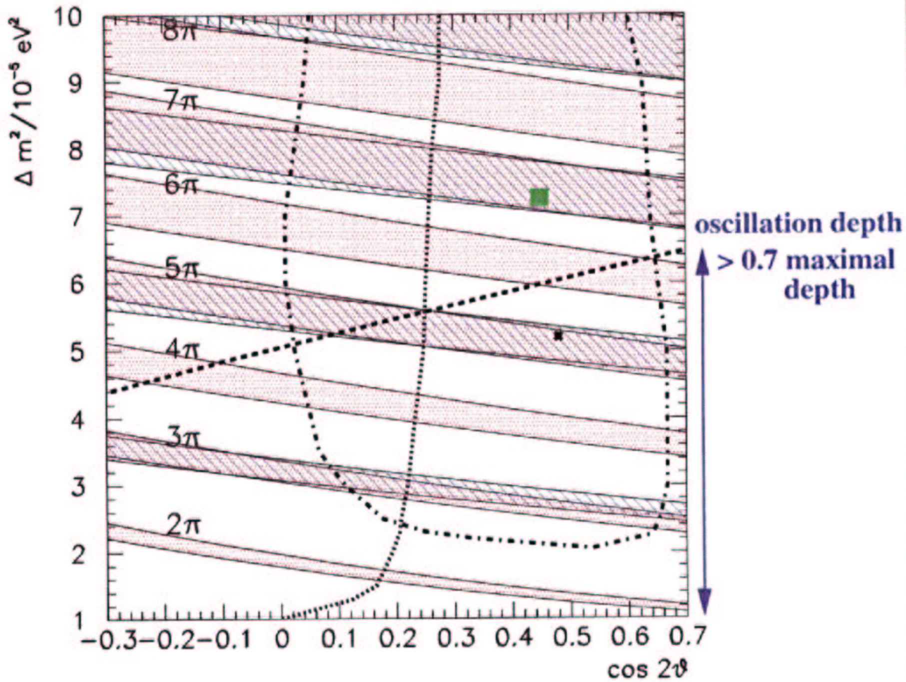


C.Lunardini and A.Yu.Smirnov, in preparation

see also: C.Lunardini and A.Yu.Smirnov, Phys.Rev.D63:073009,2001

4

The differences can be accomodated for parameters in narrow bands in the LMA region:



integer phase at IMB at $E \sim 40$ MeV

half-integer phase at K2 at $E \sim 40$ MeV

LMA contour (pre–KamLand)

LMA best fit point (post–KamLand)

5

perspective: what do we need?
what would we like?

- ***Experiments:***
  - large ν_e detectors
  - long-lived dedicated observatories

    Large volumes (HyperK, UNO, Titand ...)

    joint activity of different experiments (SNEWS - early alert)

- ***Theory: numerical simulations***

? consensus

? exploding models

- simulation to later times (~ 10 s)

proposal: SuperKamiokande upgrade

by J.Beacom and M.Vagins, in preparation

see talk by M.Vagins at Noon2003 conference, Kanazawa
http://www-sk.icrr.u-tokyo.ac.jp/noon2003/transparencies

the idea: enrich SuperK with Gadolinium
(~ 100 tons of $GdCl_3$)
cheap ($\sim \$ 4$/Kg) and harmless

effects: tag the $\bar{\nu}_e$ events individually using neutron capture

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

$$\longrightarrow Gd \rightarrow 8MeV\gamma \; cascade$$

physics implications:

- enhanced sensitivity to:
  relic supernova $\bar{\nu}_e$ ($\sim$ 5/year in SK)
  $\bar{\nu}_e$ from the sun
- supernova burst: study ν_e signal:
  $\nu_e +^{16} O \rightarrow e^- +^{16} F$

by subtracting the $\bar{\nu}_e$ events (~ 8000)

→ best ν_e detector:

~ 600 events for galactic SN

Conclusions:

1. Supernova neutrinos can be used to probe the 13-mixing angle and the neutrino mass hierarchy
2. This requires the inclusion of large astrophysical uncertainties
3. It is possible to identify and study analytically observables in which the astrophysical uncertainties largely cancel
4. While the establishment of the mass hierarchy appears difficult, strong (conditional) bounds on θ_{13} can be put