Supernova: the cosmic competitor of neutrino factories

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Physics with

Atmospheric Neutrinos and Neutrinos from Muon Storage Rings

IIT Mumbai, August 2, 2005

Competition and complementarity

- The USP's of a neutrino factory
  - Determination of mass hierarchy (normal vs inverted)
  - Measurement of Θ_{13}: reach to very low values
  - Observation of leptonic CP violation
- Neutrinos from a galactic SN $\Rightarrow$
  - Determination of mass hierarchy (normal vs inverted)
  - Bounds on Θ_{13} in the range $\sin^2\Theta_{13} \sim 10^{-3}$–$10^{-5}$
- Neutrino factory $\oplus$ SN:
  - Understanding of SN astrophysics
  - Tracking of SN shock wave

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SN: A natural phenomenon where extremely low values of Θ_{13} make a huge difference !!

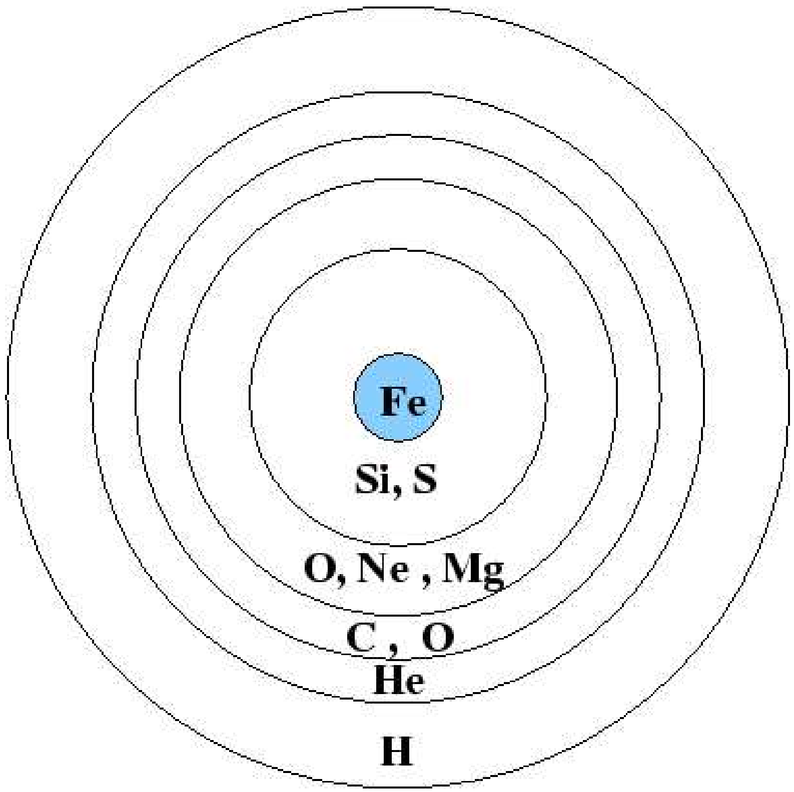
$\Rightarrow$ Motivation for trying to measure Θ_{13} even if it is very small

Neutrino experiment at a cosmic scale

- SN as a free (but rarely operational) neutrino factory
  - SN core: all ν and $\bar{\nu}$ species produced
  - Primary fluxes and their model dependence
- Very long baseline
  - Flavour conversions in SN mantle and envelope
  - Propagation through interstellar space
  - Oscillations inside the Earth
- Extracting Θ_{13} and mass hierarchy in model independent ways
  - Comparison between neutrino fluxes at two detectors
  - Identification of "Earth oscillation frequencies"
  - Detection of neutrino signatures of shock wave propagation

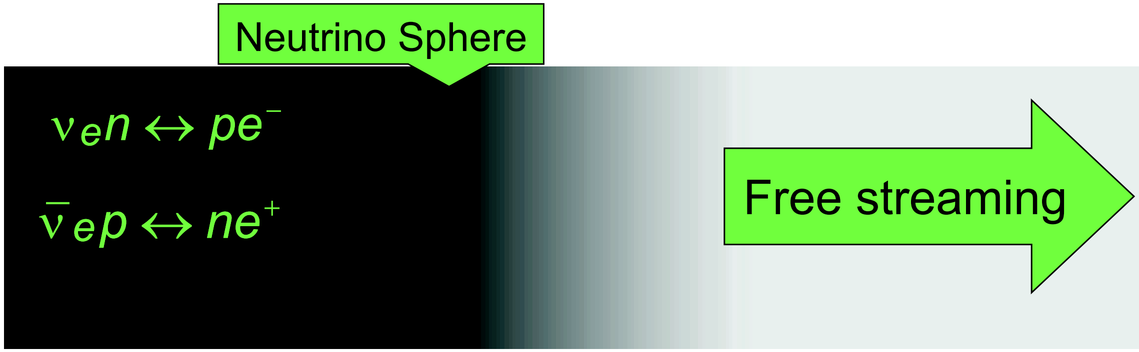
The neutrino factory setup

Type II (core collapse) supernova:

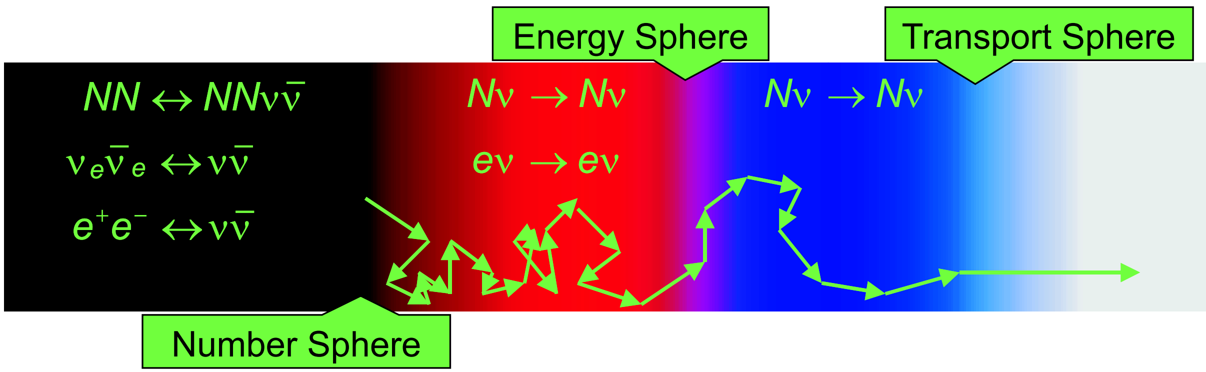


Before the collapse

- Neutrinos trapped inside "neutrinospheres" around $\rho \sim 10^{10}$g/cc
- Free-streaming when $\rho \lesssim 10^{10}$g/cc



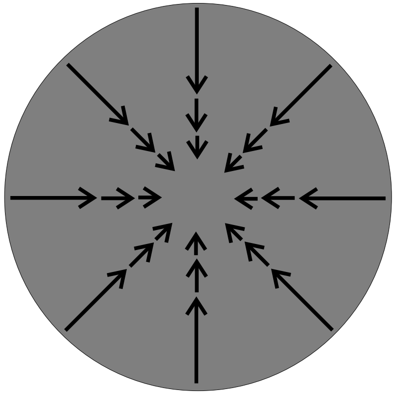
$\nu_e, \bar{\nu}_e$



$\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$

The collapse...

- Gravitational core collapse



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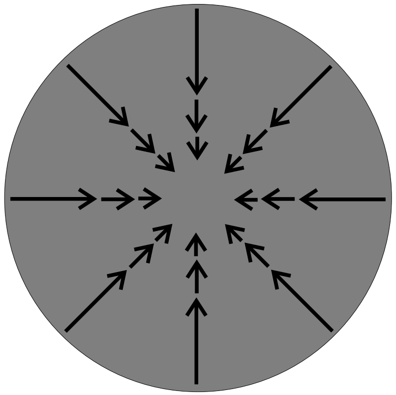
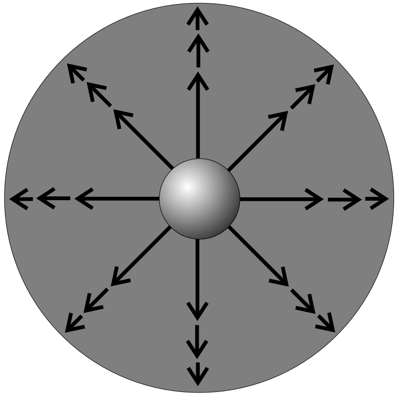


- Generation of a shock wave



The SN saga continues...

- Neutronization burst:
  Shock wave breaks up the nuclei $\Rightarrow e^-$ capture enhanced
  ν_e emitted at the ν_e neutrinosphere.
  Duration: The first $\sim$ 10 ms

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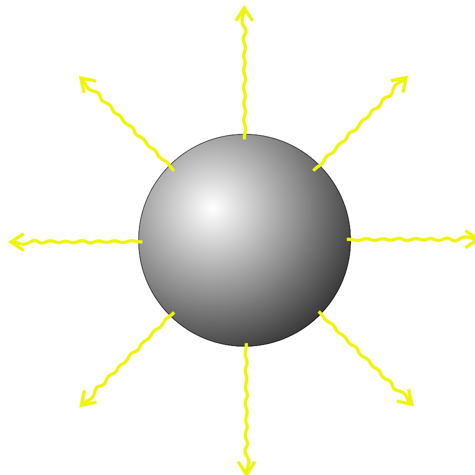
- Cooling through neutrino emission: $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$
  Duration: About 10 sec
  Emission of 99% of the SN energy in neutrinos

Can be used for “pointing” to the SN
in advance. (“Early warning”)
(pointing accuracy: $\lesssim 10^\circ$ at SK with 10kpc)



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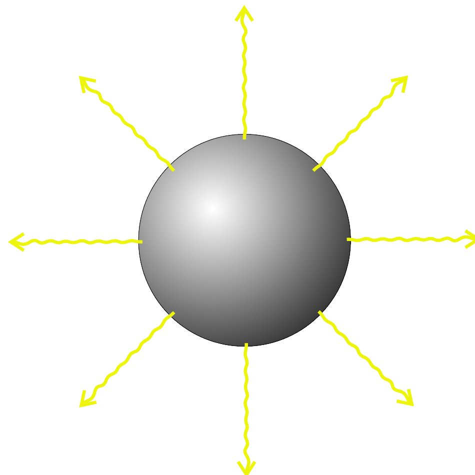

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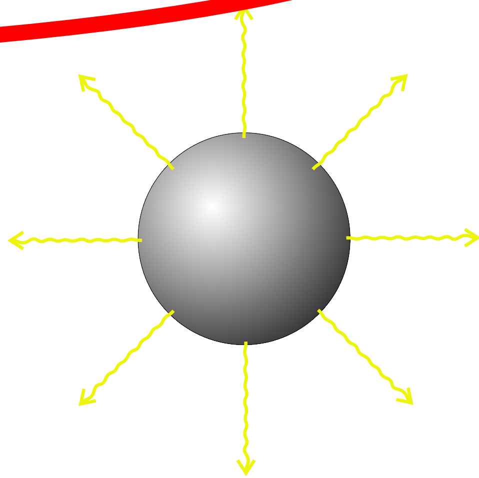

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Initial neutrino spectra

Neutrino fluxes:

$$F^0_{\nu_i} = \frac{\Phi_0}{E_0} \frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)} \left(\frac{E}{E_0}\right)^{\alpha} \exp\left[-(\alpha+1)\frac{E}{E_0}\right]$$

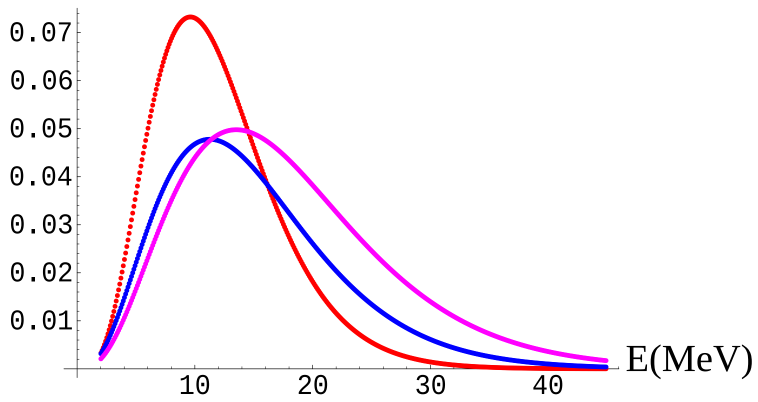
E_0, α: in general time dependent

Known properties of the spectra:

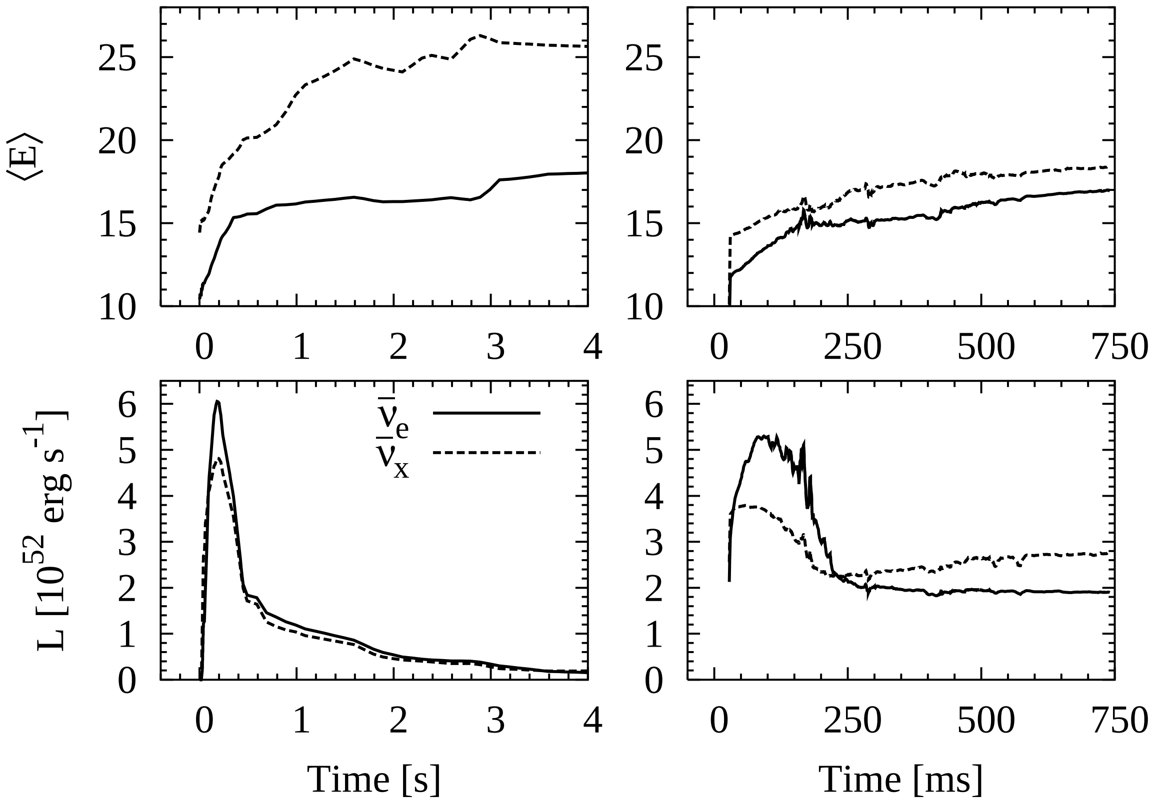
- Energy hierarchy: $E_0(\nu_e) < E_0(\bar{\nu}_e) < E_0(\nu_x)$
- Spectral pinching: $\alpha_{\nu_i} > 2$

$E_0(\nu_e) \approx 10$–12 MeV
$E_0(\bar{\nu}_e) \approx 13$–$16$ MeV
$E_0(\nu_x) \approx 15$–20 MeV
$\alpha_{\nu_i} \approx 2$–4

G. G. Raffelt, M. T. Keil, R. Buras, H. T. Janka and M. Rampp, astro-ph/0303226



Flavor-dependent neutrino fluxes

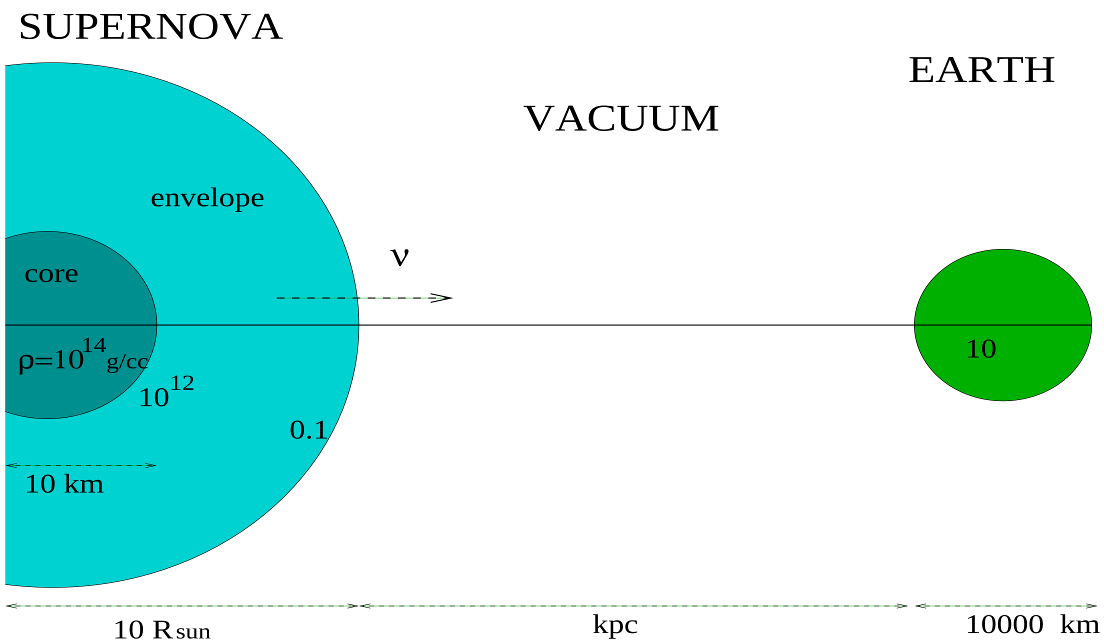


solid line: $\bar{\nu}_e$
dotted line: $\bar{\nu}_x$

Model	$\langle E_0(\nu_e)\rangle$	$\langle E_0(\bar{\nu}_e)\rangle$	$\langle E_0(\nu_x)\rangle$	$\frac{\Phi_0(\nu_e)}{\Phi_0(\nu_x)}$	$\frac{\Phi_0(\bar{\nu}_e)}{\Phi_0(\nu_x)}$
Garching (G)	12	15	18	0.8	0.8
Livermore (L)	12	15	24	2.0	1.6

G. G. Raffelt, M. T. Keil, R. Buras, H. T. Janka and M. Rampp, astro-ph/0303226
T. Totani, K. Sato, H. E. Dalhed and J. R. Wilson, Astrophys. J. 496, 216 (1998)

The long baseline



- SN core ($\rho \geq 10^{10}$ g/cc)
- SN mantle and envelope ($\rho \sim 10^5 - 10^{-1}$ g/cc)
- Interstellar medium ($\rho \approx 0$ g/cc)
- Earth matter ($\rho \geq$ 5 – 10 g/cc)

Matter effects crucial !!!

2-ν level crossing

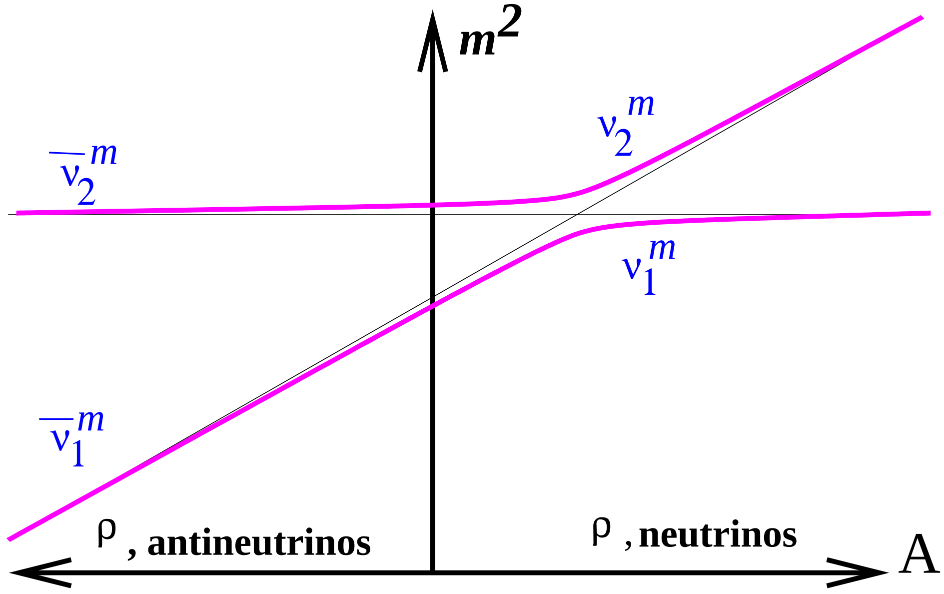
- Effective Hamiltonian:

$$H = \frac{1}{4E}\begin{pmatrix} -\Delta m^2 \cos 2\Theta + 2A & \Delta m^2 \sin 2\Theta \\ \Delta m^2 \sin 2\Theta & \Delta m^2 \cos 2\Theta \end{pmatrix}$$

$(A = 2E\, V_{cc})$

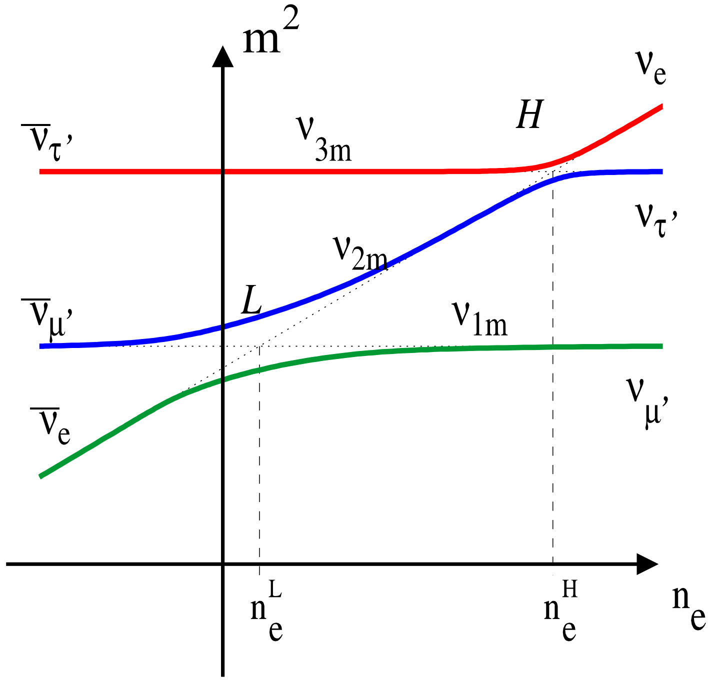
- Eigenvalues:

$$\frac{m_i^2}{2E} = \frac{1}{2E}\left[\frac{A}{2} \mp \sqrt{(\Delta m^2 \cos 2\Theta - A)^2 + (\Delta m^2 \sin 2\Theta)^2}\right]$$

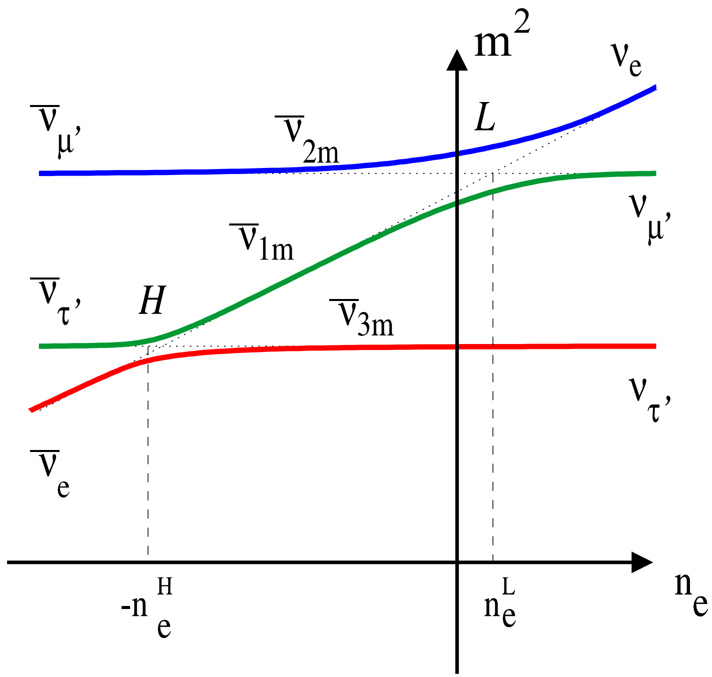


3-ν level crossings

Normal mass hierarchy

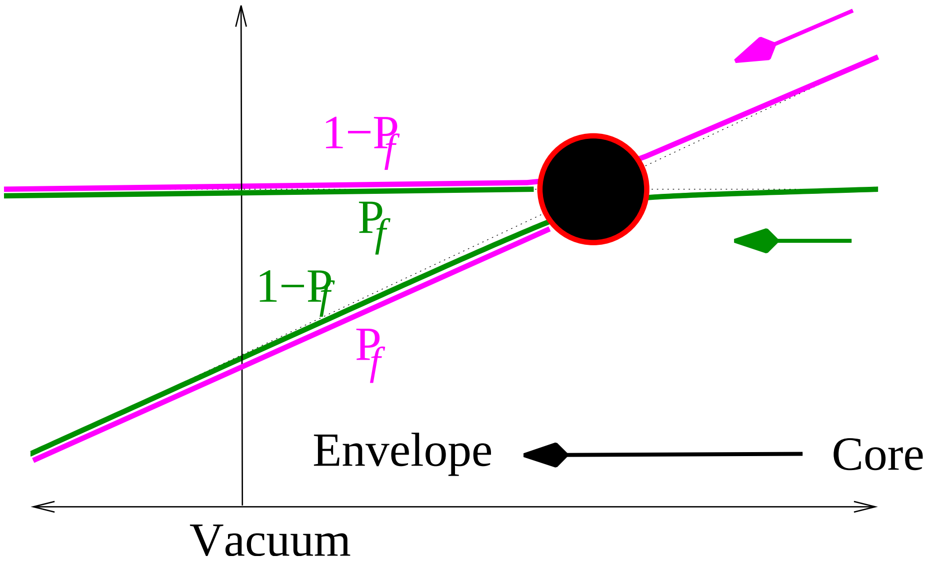


Inverted mass hierarchy



- H resonance: $(\Delta m^2_{\rm atm}, \Theta_{13})$, $\rho \sim 10^3$–10^4 g/cc
- L resonance: $(\Delta m^2_{\odot}, \Theta_{\odot})$, $\rho \sim$ 10–100 g/cc
- Δm^2 hierarchy $\Rightarrow$ Independent dynamics at resonances

Adiabaticity at resonance



$$P_f \approx exp\left(-\frac{\pi}{2}\gamma\right)$$

Landau'1932, Zener'1932

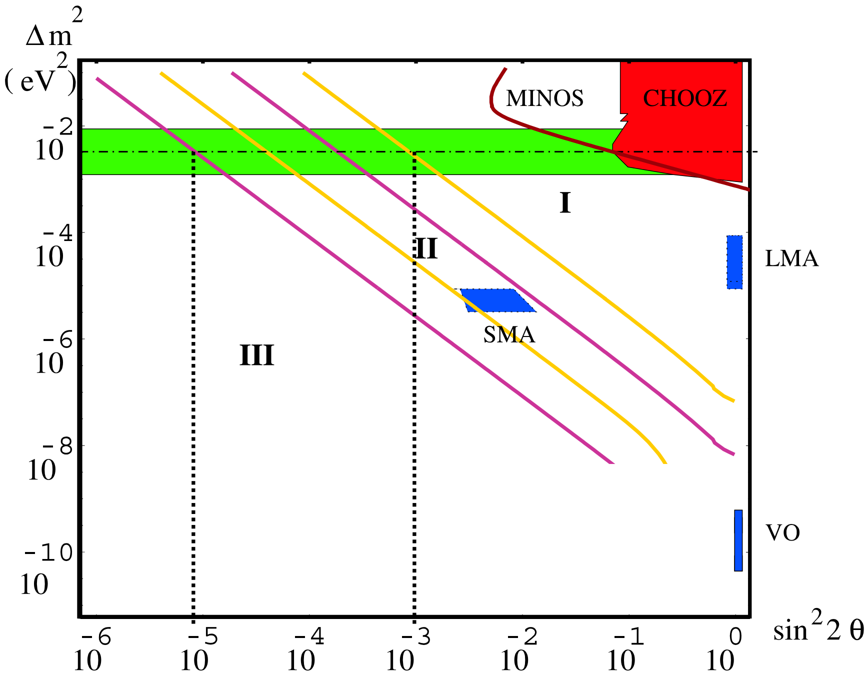
$$\gamma \gg 1 \Rightarrow P_f \ll 1 \Rightarrow$$

Adiabatic resonance

$$\gamma \equiv \frac{\Delta m^2}{2E}\frac{\sin^2 2\Theta}{\cos 2\Theta}\left(\frac{1}{n_e}\frac{dn_e}{dr}\right)^{-1}$$

Dependence on: Δm^2, mixing angle, density profile

Adiabaticity at H and L resonances



- L always adiabatic
- H adiabatic for $|U_{e3}|^2 \gtrsim 10^{-3}$, non-adiabatic for $|U_{e3}|^2 \lesssim 10^{-3}$
- H in ν_e for normal hierarchy
  H in $\bar{\nu}_e$ for inverted hierarchy

SN neutrino spectra sensitive to

- $|U_{e3}|^2 \gtrsim 10^{-3}$ or $|U_{e3}|^2 \lesssim 10^{-3}$
- Normal mass hierarchy or inverted mass hierarchy

AD, A. Smirnov, PRD 62, 033007 (2000)

Fluxes arriving at the Earth

Mixture of initial fluxes:

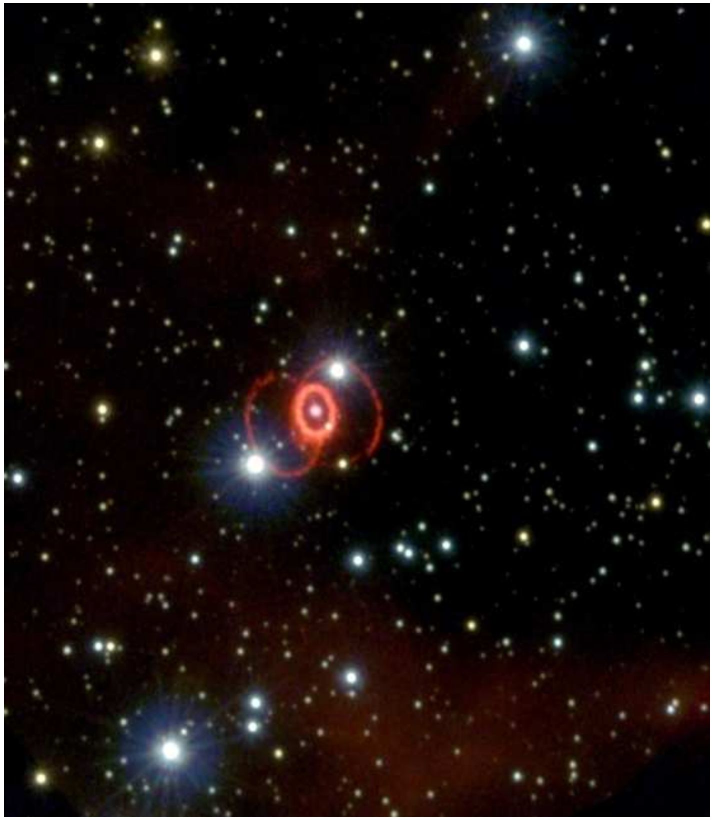
$$
\begin{aligned}
F_{\nu_e} &= pF^0_{\nu_e} + (1-p)F^0_{\nu_x} \; , \\
F_{\bar{\nu}_e} &= \bar{p}F^0_{\bar{\nu}_e} + (1-\bar{p})F^0_{\nu_x} \; , \\
4F_{\nu_x} &= (1-p)F^0_{\nu_e} + (1-\bar{p})F^0_{\bar{\nu}_e} + (2+p+\bar{p})F^0_{\nu_x} \; .
\end{aligned}
$$

Survival probabilities in different scenarios:

Case	Hierarchy	$\sin^2\Theta_{13}$	p	$\bar{p}$
A	Normal	$\gtrsim 10^{-3}$	0	$\cos^2\Theta_\odot$
B	Inverted	$\gtrsim 10^{-3}$	$\sin^2\Theta_\odot$	0
C	Any	$\lesssim 10^{-5}$	$\sin^2\Theta_\odot$	$\cos^2\Theta_\odot$

- Sensitivity to extremely low values of $\sin^2\Theta_{13}$!!

SN87A



(Hubble image)

- Confirmed the SN cooling mechanism through neutrinos
- Number of events too small to say anything concrete about neutrino mixing
- Some constraints on SN parameters obtained

Detecting a galactic SN

Events expected at Super-Kamiokande with a SN at 10 kpc:

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

Some useful reactions at other detectors:

- Carbon-based scintillator: $\nu + {}^{12}C \to \nu + X + \gamma$ (15.11 MeV)
- Liquid Ar: $\nu_e + {}^{40}Ar \to {}^{40}K^* + e^-$

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INO/ICAL:

- Energy of SN ν too low to produce muons through CC
- *¿ ¿ Can something be done a la IceCube ??*

Identifying neutrino mixing scenario

Problems:

- Poorly known initial spectra
- Only final $\bar{\nu}_e$ spectrum cleanly available (ν_e if we have a large liquid Ar detector).
- Need to find observables independent of the models of primary spectra

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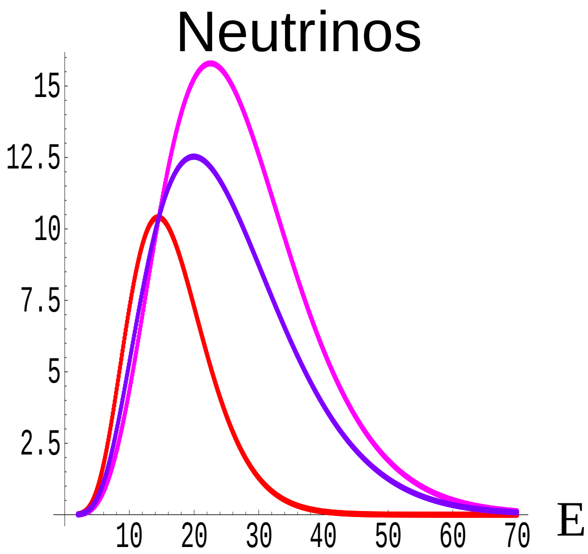
Solutions:

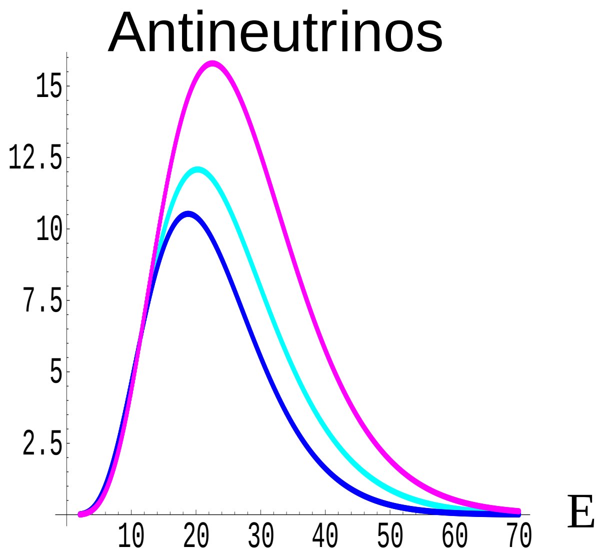
- Identify Earth matter effects if neutrinos pass through the Earth
- Detect neutrino signatures of the shock wave propagation

Earth Matter Effects

Pure or mixed spectrum ?



$(\nu_e, \nu_x, \text{mixed } \nu)$



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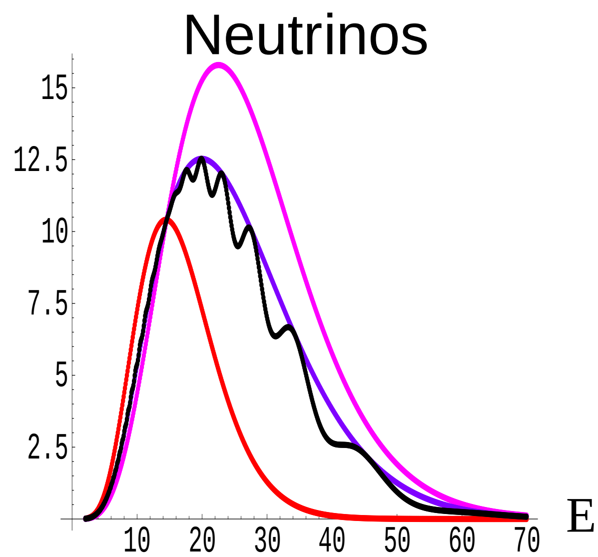
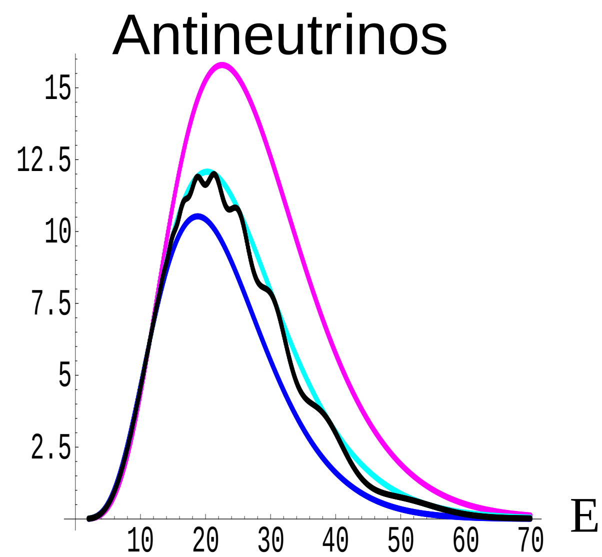


$(\nu_e, \nu_x,$ mixed $\nu)$



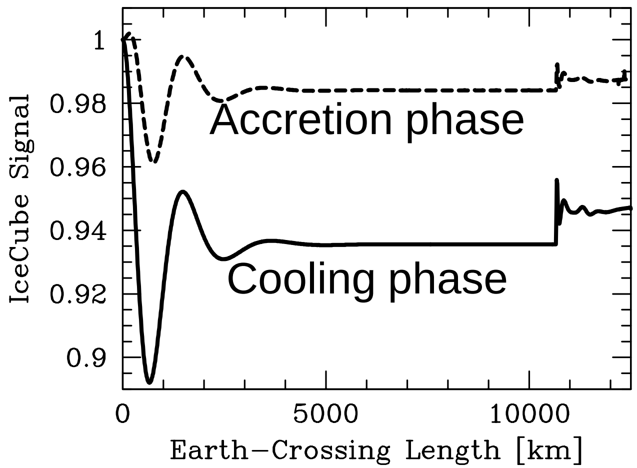
$(\bar{\nu}_e, \bar{\nu}_x,$ mixed $\bar{\nu})$

⊕ Earth effects

- Total number of events (in general) decreases
  - Compare signals at two detectors
- “Earth effect” oscillations are introduced
  - In ν_e if inverted hierachy OR $\sin^2\Theta_{13} < 10^{-3}$
  - In $\bar{\nu}_e$ if normal hierachy OR $\sin^2\Theta_{13} < 10^{-3}$
  - Can identify oscillations at a single detector

IceCube as a co-detector with SK/HK

- IceCube primarily meant for neutrinos with energy $\gtrsim 150$ GeV
- The number of Cherenkov photons increases beyond statistical background fluctuations during a SN burst
- This signal can be determined to a statistical accuracy of $\sim 0.25\%$ for a SN at 10 kpc.
- The Earth effects may change the signal by ~ 0–10%.



- The extent of Earth effects changes by 3–4 % between the accretion phase (first 0.5 sec) and the cooling phase.
- Absolute calibration not essential.

AD, M. Keil, G. Raffelt, JCAP 0306:005 (2003)

At a single detector

(Identifying Earth oscillation frequency)

$$F_{\bar{\nu}_e} = \sin^2\Theta_{12} F^0_{\nu_x} + \cos^2\Theta_{12} F^0_{\bar{\nu}_e} + \Delta F^0 \bar{A}_\oplus \sin^2(\overline{\Delta m^2_\oplus L} y)$$

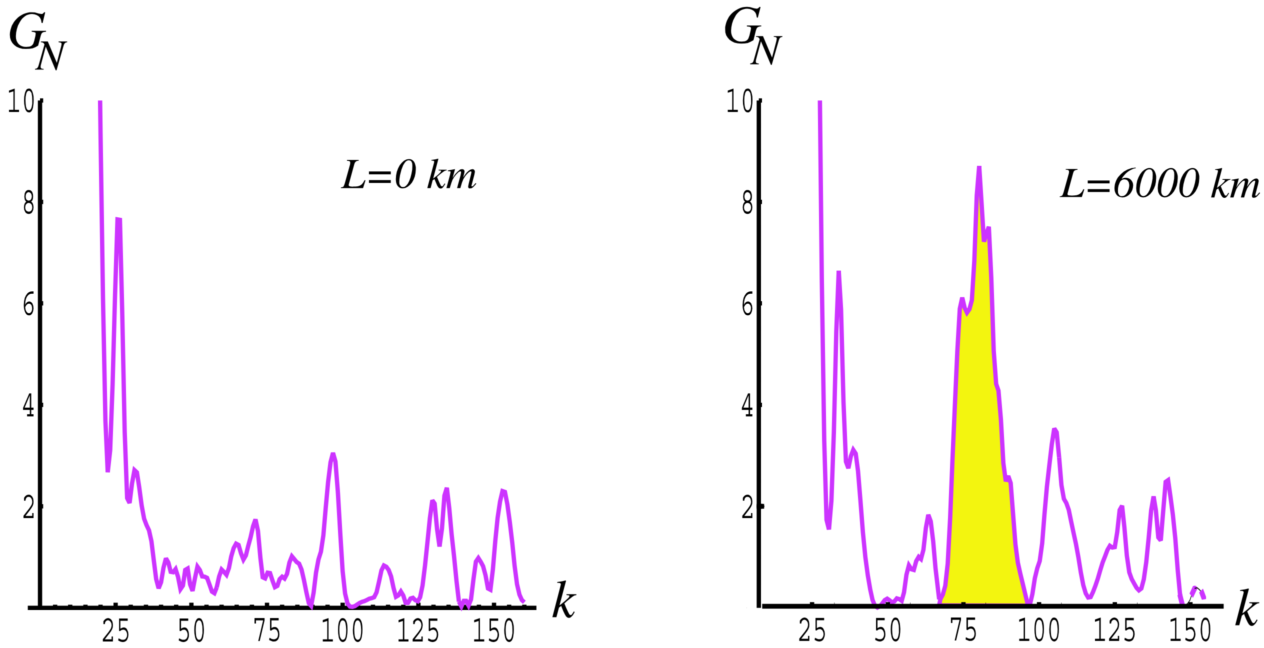
$$(F^0_{\bar{\nu}_e} - F^0_{\nu_x}) \qquad \sin 2\bar{\Theta}^\oplus_{12} \sin(2\bar{\Theta}^\oplus_{12} - 2\Theta_{12}) \qquad (12.5/E)$$

Oscillation frequency: $k_\oplus \equiv 2\overline{\Delta m^2_\oplus L}$

- The highest frequency in the “inverse energy” dependence of the spectrum
- Completely independent of the primary neutrino spectra
- Depends only on solar oscillation parameters, Earth density and the distance travelled through the Earth
- Can be approximated to within 10% by $2\Delta m^2_\odot L$

Fourier Transform

Power spectrum: $G_N(k) = \frac{1}{N} \left| \sum_{events} e^{iky} \right|^2$

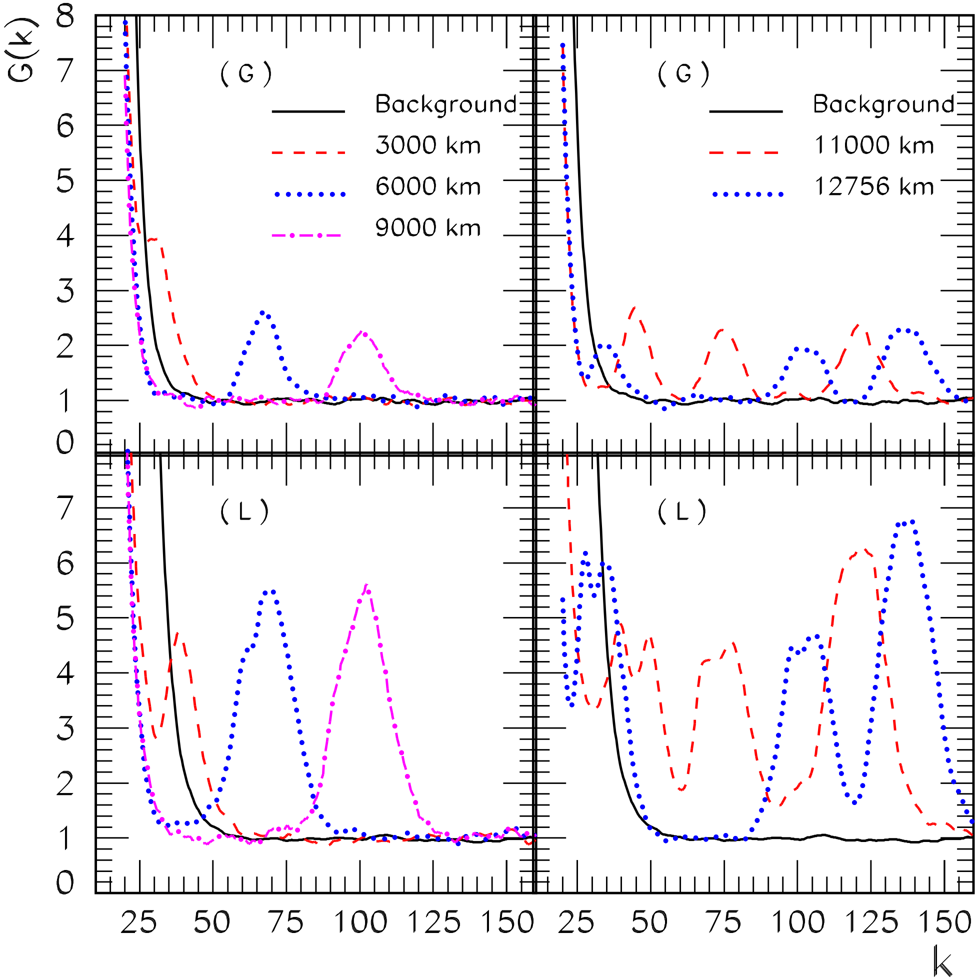


- Energy resolution is a crucial factor
- Scintillation detector: a few thousand events
- Water Cherenkov detector: a few ten thousand events

AD, M. Keil, G. Raffelt, JCAP 0306:006 (2003)

At a scintillation detector

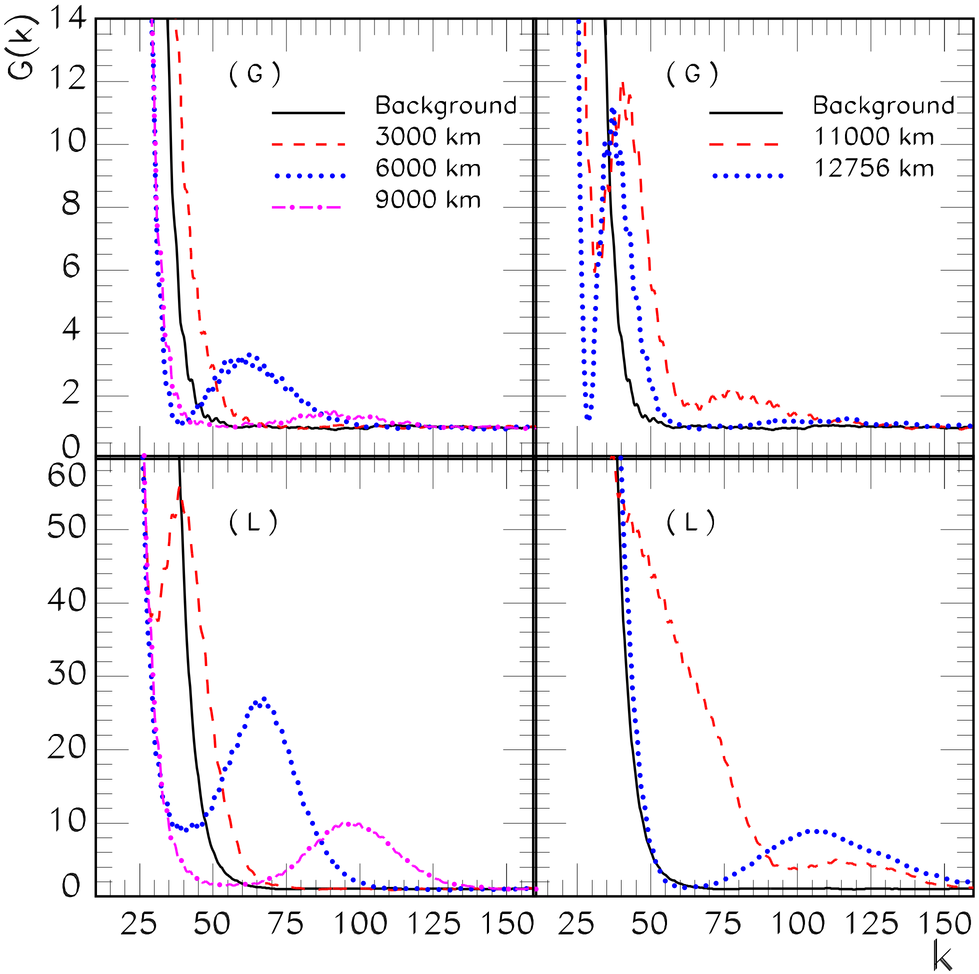
- Model independence of peak positions:



AD, M. Kachelrieß, G. Raffelt, R. Tomàs, JCAP 0401:004 (2004)

At a water Cherenkov detector

- High-k suppression:



AD, M. Kachelrieß, G. Raffelt, R. Tomàs, JCAP 0401:004 (2004)

Earth effects ⇒ Fourier peaks

- Observation of a Fourier peak in $\bar{\nu}_e$ ⇒
  Eliminate [Inverted hierarchy $\oplus$ "large" Θ_{13}] (scenario B)
- Observation of a Fourier peak in ν_e (liquid Ar) ⇒
  Eliminate [Normal hierarchy $\oplus$ "large" Θ_{13}] (scenario A)

Earth effects ⇒ Fourier peaks

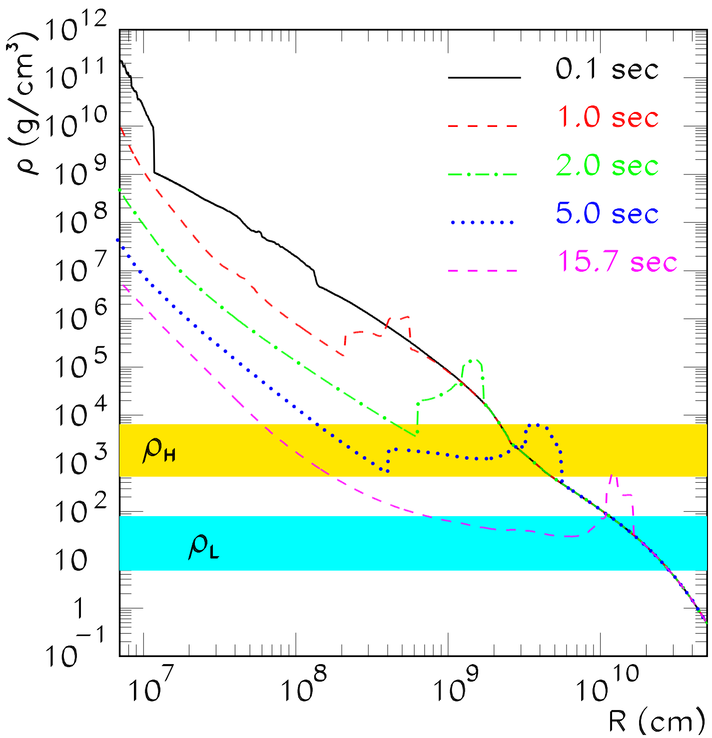
- Observation of a Fourier peak in $\bar{\nu}_e \Rightarrow$
  Eliminate [Inverted hierarchy $\oplus$ "large" Θ_{13}] (scenario B)
- Observation of a Fourier peak in ν_e (liquid Ar) $\Rightarrow$
  Eliminate [Normal hierarchy $\oplus$ "large" Θ_{13}] (scenario A)

Things to note:

- No model dependence on primary spectra
- Presence of the Fourier peak sufficient to distinguish between mixing scenarios
- Strength of the peak contains information on details of primary spectra

Shock wave and Θ_{13}

Shock wave and adiabaticity breaking

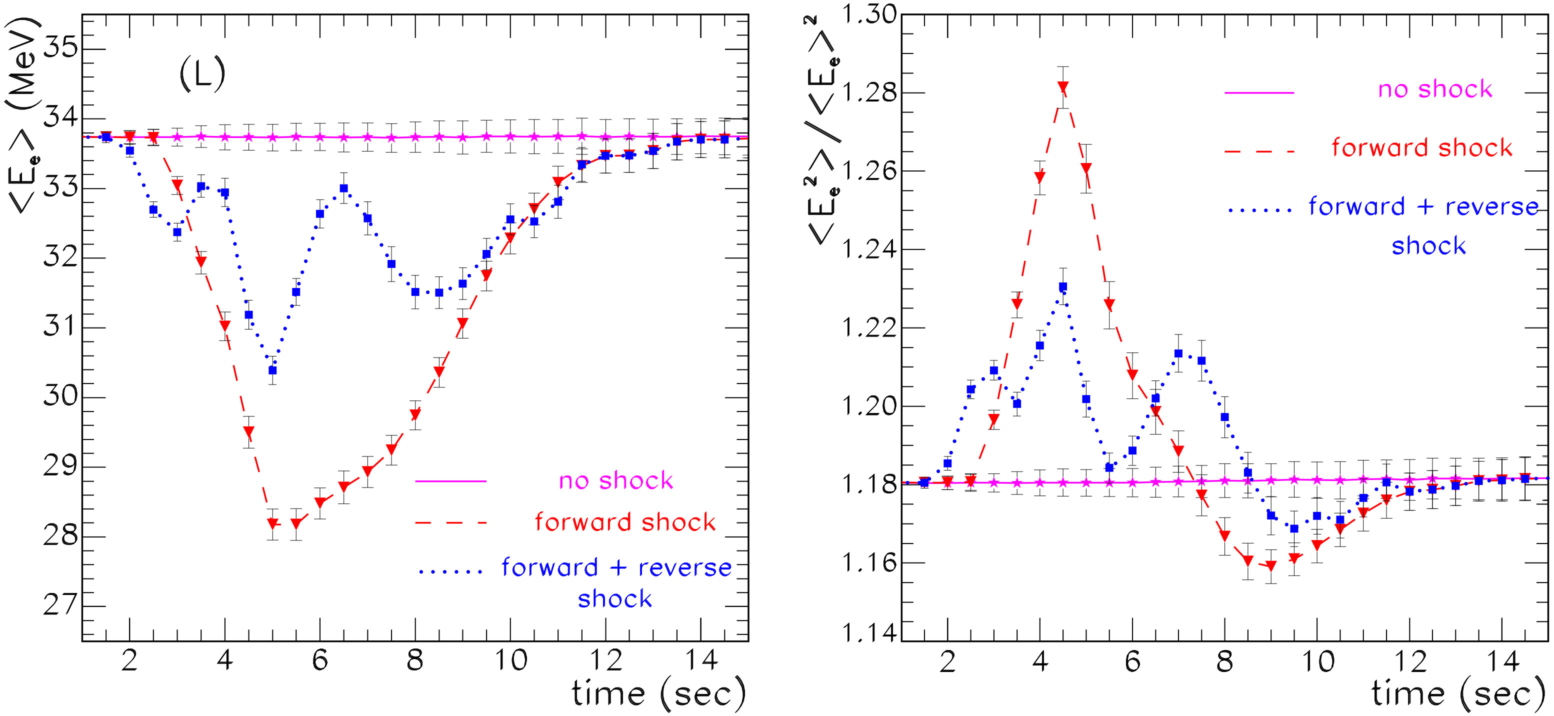


- When shock wave passes through a resonance region, adiabatic resonances may become non-adiabatic for some time
  scenario A $\to$ scenario C
  scenario B $\to$ scenario C
- May cause sharp changes in the final spectra even if the primary spectra are unchanged / smoothly changing

R. C. Schirato, G. M. Fuller, astro-ph/0205390

G. L. Fogli, E. Lisi, D. Montanino and A. Mirizzi, PRD 68, 033005 (2003)

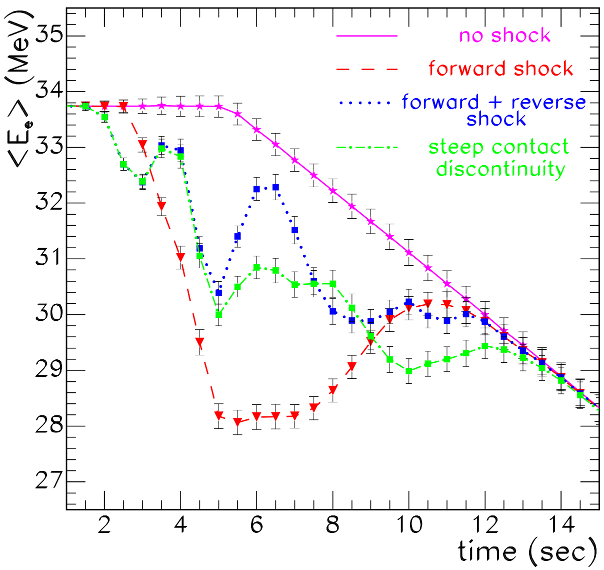
At a water Cherenkov (HK)

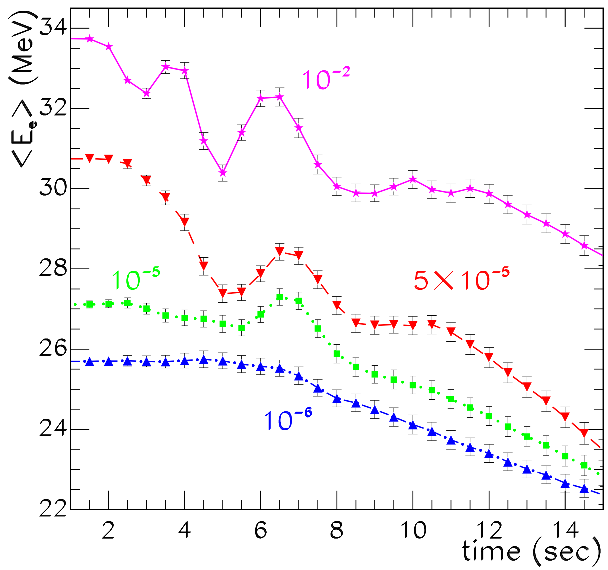


- "Single (Double) dip" feature in $\langle E_e \rangle$ for "Forward (+ Reverse) shock"
- "Single (Double) peak" feature in $\langle E_e^2 \rangle / \langle E_e \rangle^2$ for "Forward (+ Reverse) shock"

R. Tomás, M. Kachelrieß, G. Raffelt, AD,
H. T. Janka, L. Scheck, JCAP09(2004)015

Single/double dip

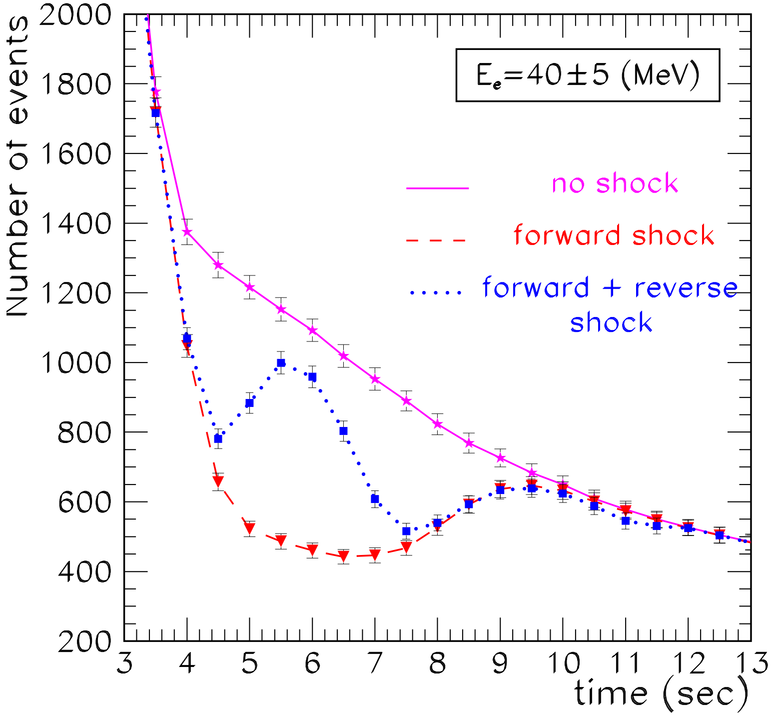


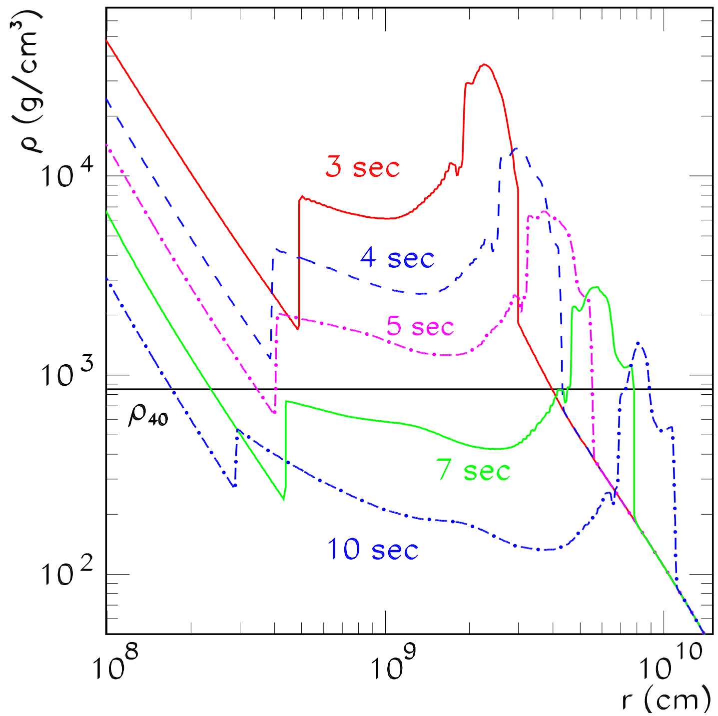


- "Single/double dip" robust under
  - monotonically decreasing average energy
  - features like "contact discontinuity"
- "Single/double dip" visible for
  - $\sin^2 2\Theta_{13} \gtrsim 10^{-5}$
  - In ν_e for normal hierarchy
  - In $\bar{\nu}_e$ for inverted hieratchy

Tracking the shock fronts

Example:





- At $t \approx 4.5$ sec, (reverse) shock at ρ_{40}
- At $t \approx 7.5$ sec, (forward) shock at ρ_{40}
- Multiple energy bins $\Rightarrow$ the times the shock fronts reach different densities of $\rho \sim 10^3$–10^4 g/cc

Looking for Θ_{13} in SN signals

Observables to look for:

LUM Difference in luminosity ratios of HK and IceCube in the accretion phase and cooling phase (Earth effect)

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Θ_{13} values displaying the above signals:

- $\sin^2 \Theta_{13} \gtrsim 10^{-3}$: DIP
- $10^{-5} \lesssim \sin^2 \Theta_{13} \lesssim 10^{-3}$: LUM, FP, DIP
- $\sin^2 \Theta_{13} \lesssim 10^{-5}$: FP, DIP

$\Rightarrow$ An order-of-magnitude estimation of Θ_{13} possible

Concluding remarks

SN $\Leftrightarrow$ LBL synergy

- SN: a compelling reason to measure extremely low Θ_{13} values
- A galactic SN may reveal
  - mass hierarchy
  - an order-of-magnitude range for Θ_{13}
- Once Θ_{13} is known
  - Primary neutrino spectra reconstructed
  - Details of SN density profile and shock wave propagation around $\rho \sim 10^3$–10^4 g/cc

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Neutrino physics $\Leftrightarrow$ Astrophysics interplay

- Direct association of neutrino mixing angles with astrophysical phenomena: $\Theta_{12} \Leftrightarrow$ Solar ν, $\Theta_{23} \Leftrightarrow$ Atmospheric ν
- SN $\oplus$ long baseline experiments / neutrino factories: $\Theta_{13} \Leftrightarrow$ Supernova ν