Supernova neutrinos

production, propagation and oscillations

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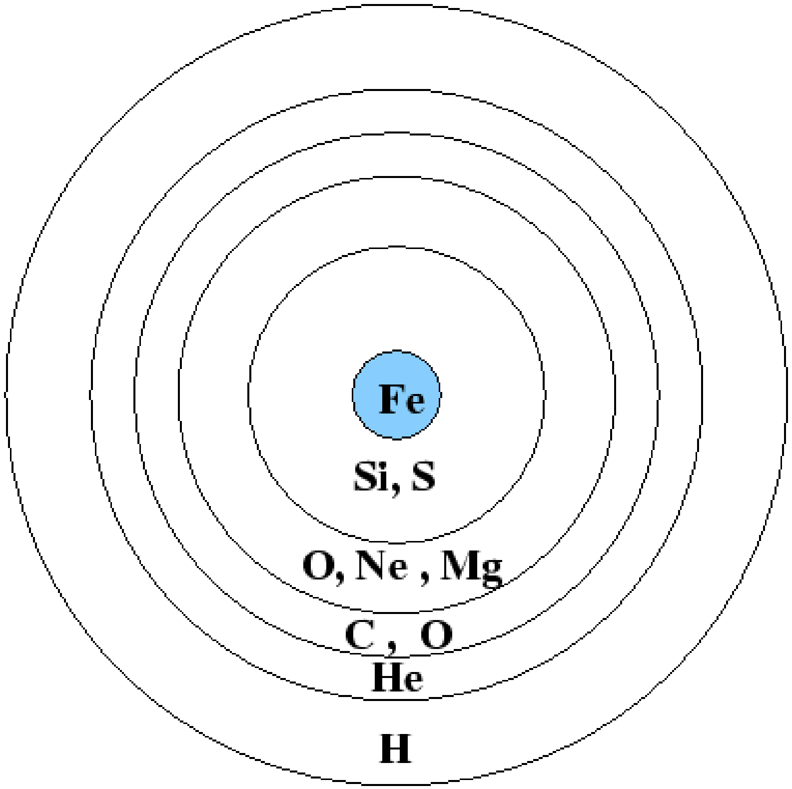
Neutrino 2004, College de France, Paris, June 19, 2004

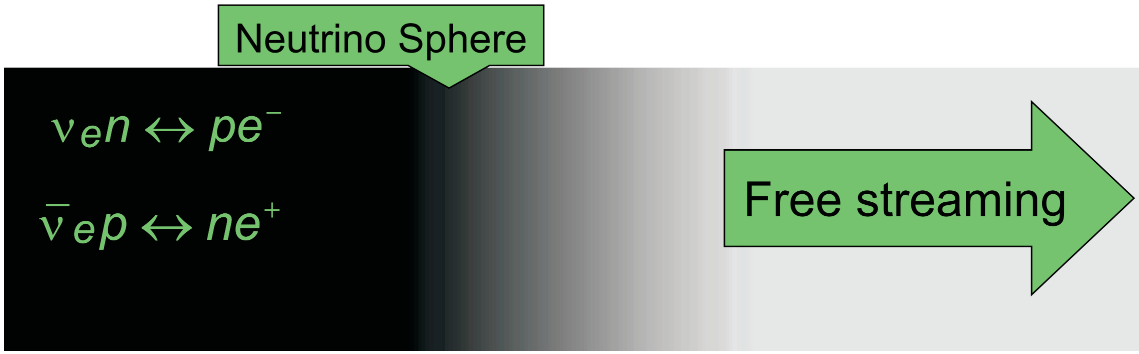
- # Production
  - Neutrino emission during the core collapse and cooling
  - Primary neutrino spectra and their model dependence
- # Propagation
  - Role of neutrinos in SN explosion
  - Neutrino flavour conversions in SN mantle and envelope
  - Neutrino mixing scenarios and observed neutrino spectra
- # Oscillations
  - Earth matter effects on neutrino spectra
  - Identification of neutrino mixing scenario
  - Learning about shock propagation

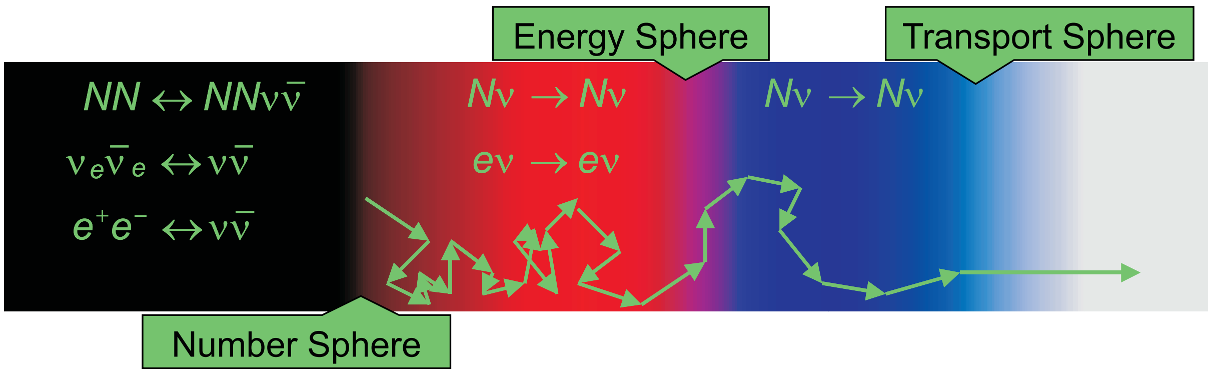
Neutrino production in core collapse SN



Before the collapse

- Neutrinos trapped inside "neutrinospheres" around $\rho \sim 10^{10}$g/cc.





- Escaping neutrinos: $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$

During the core collapse

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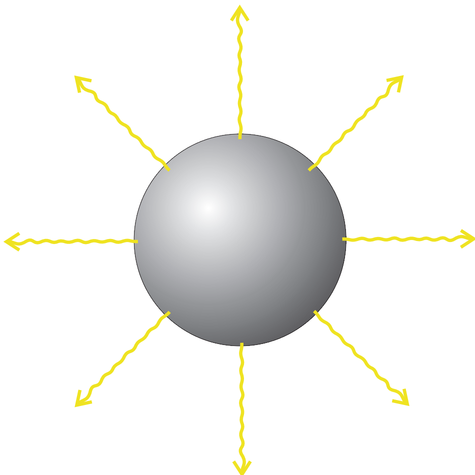
- Cooling through neutrino emission: $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$
  Duration: About 10 sec
  Emission of 99% of the SN energy in neutrinos

  Can be used for “pointing” to the SN
  in advance. (“Early warning”)
  A few hours before the explosion
  (SNEWS)



Initial neutrino spectra

Neutrino fluxes:

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

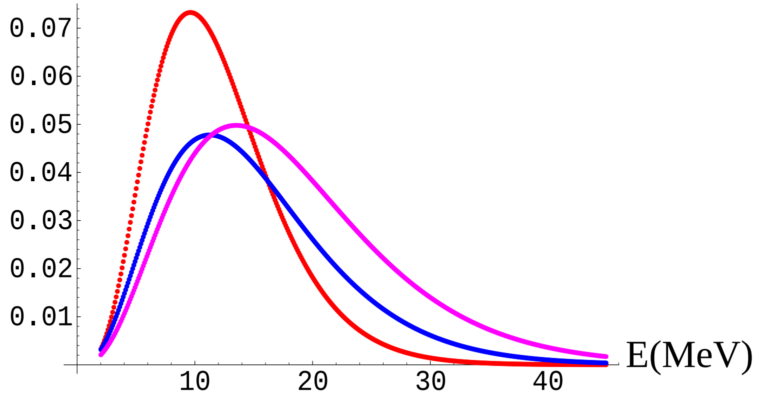
E_0, α: in general time dependent

Known properties of the spectra:

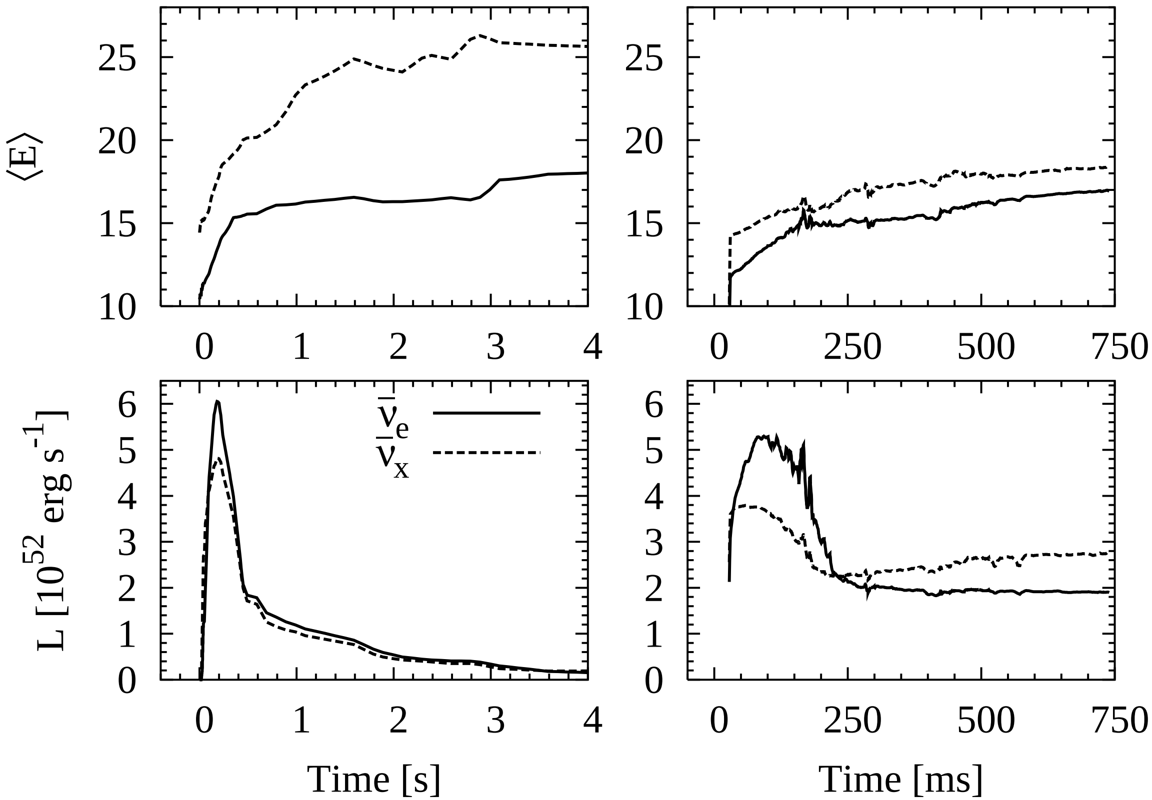
- Energy hierarchy: $E_0(\nu_e) < E_0(\bar{\nu}_e) < E_0(\nu_x)$
- Spectral pinching: $\alpha_{\nu_i} > 2$

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

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



Model dependent neutrino fluxes



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

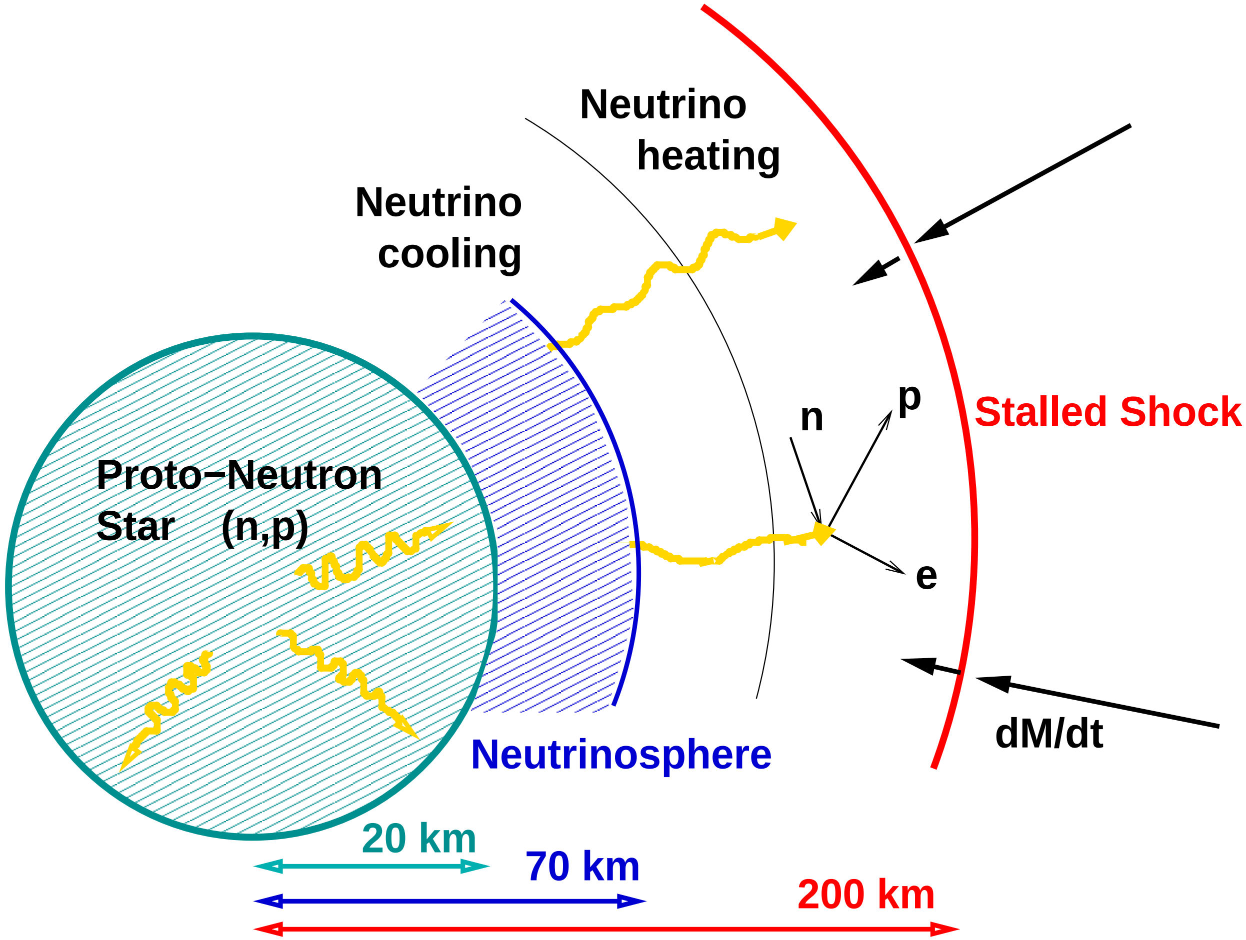
Model	$\langle E_0(\nu_e)\rangle$	$\langle E_0(\bar{\nu}_e)\rangle$	$\langle E_0(\nu_x)\rangle$	$\frac{\Phi_0(\nu_e)}{\Phi_0(\nu_x)}$	$\frac{\Phi_0(\bar{\nu}_e)}{\Phi_0(\nu_x)}$
Garching (G)	12	15	18	0.8	0.8
Livermore (L)	12	15	24	2.0	1.6

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)

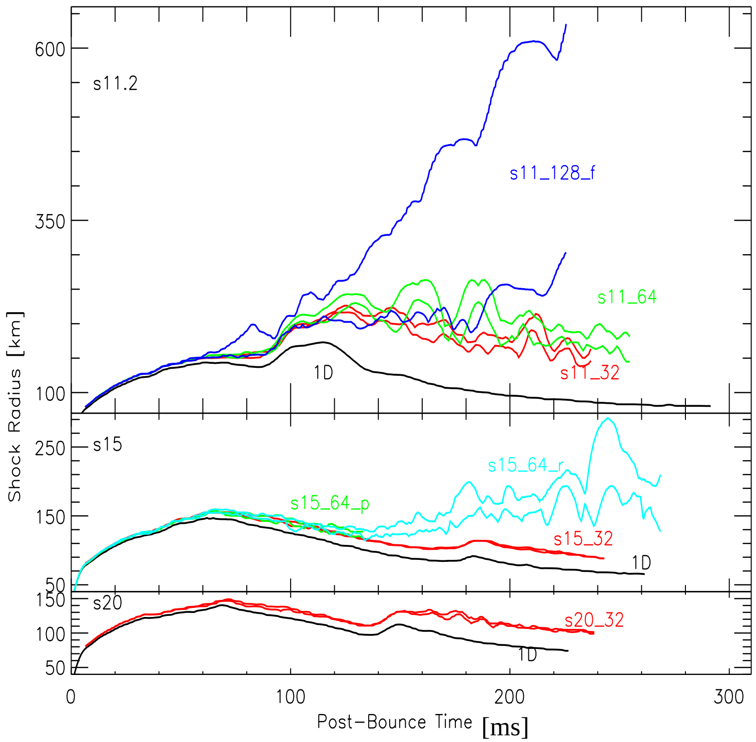
Neutrino propagation inside SN

Role of neutrinos in explosion



- Neutrino heating essential, but not enough
- No spherically symmetric (1-D) simulations show robust explosions

Ingradients required for explosion

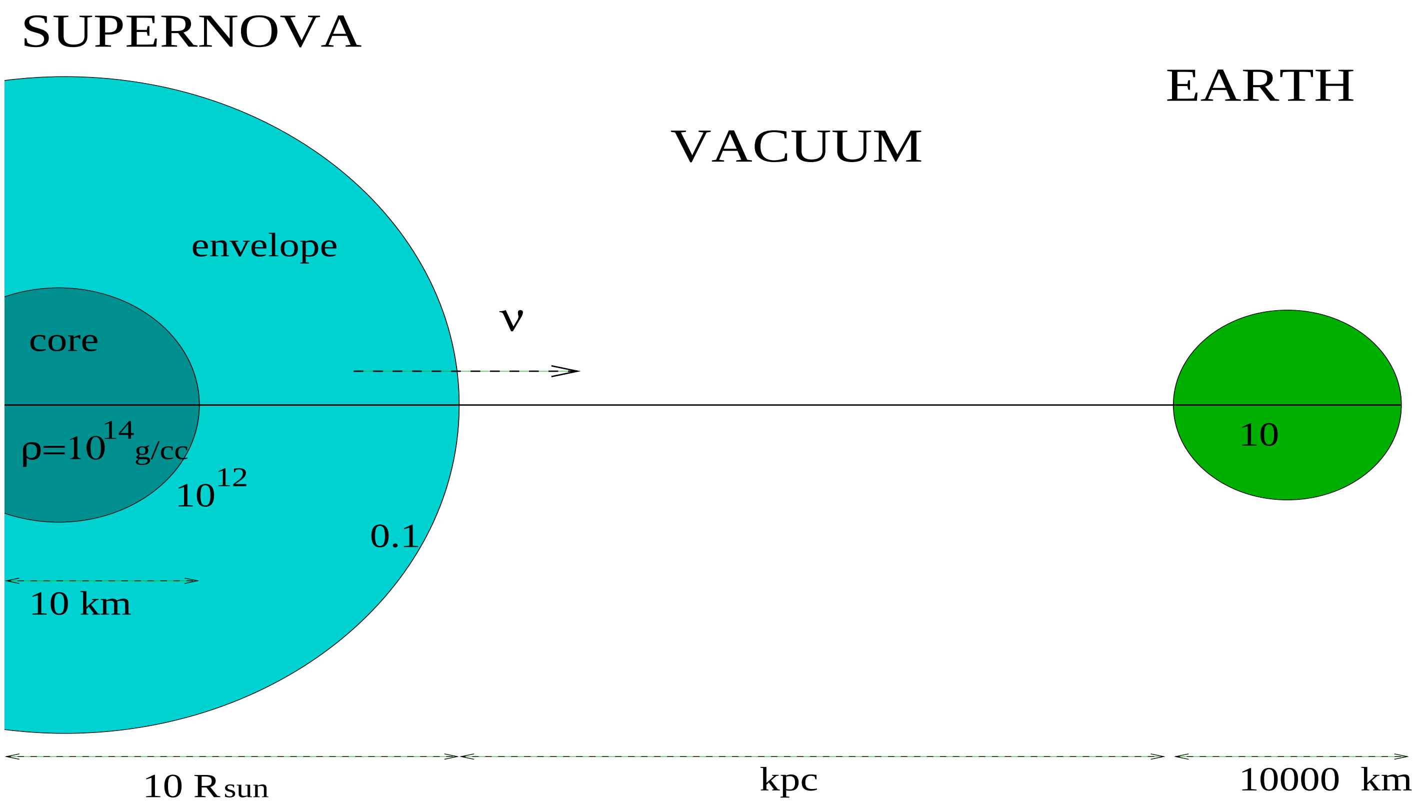


R. Buras, H.-T. Janka, M. Rampp, K. Kifonidis, astro-ph/0303171

- Neutrino heating: higher neutrino opacity
- Large scale convenction modes
- Stiffer equation of state for the core
- Rotation of the star

O. E. Bronson Messer, S. Bruenn, C. Cardall, M. Liebendoerfer, A. Mezzacappa, W. Raphael Hix, F.-K. Thielemann *et al*

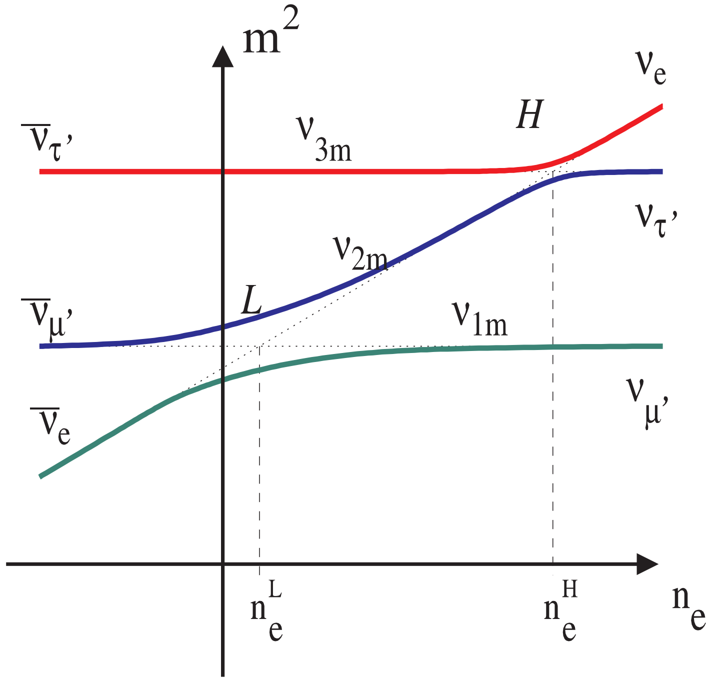
Propagation through matter



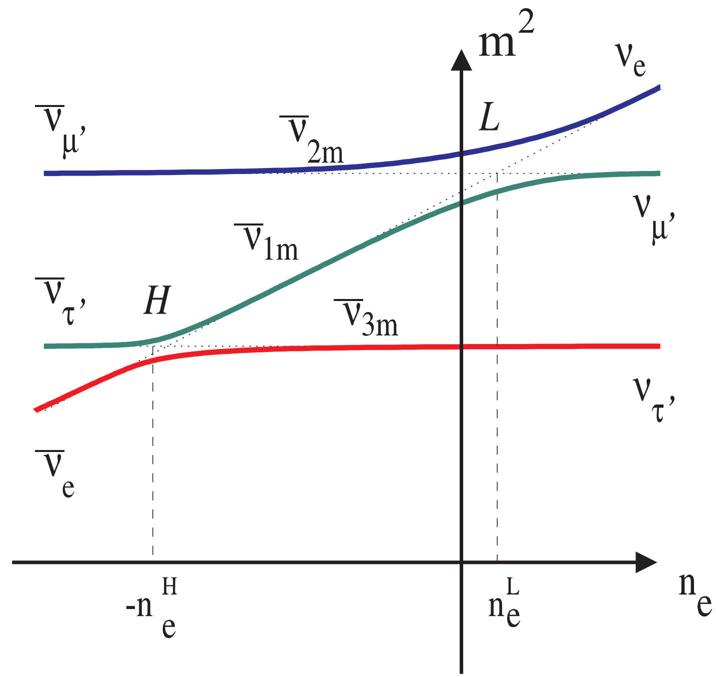
- Matter effects on neutrino mixing crucial
- Flavor conversions at resonances / level crossings

Level crossings during propagation

Normal mass hierarchy

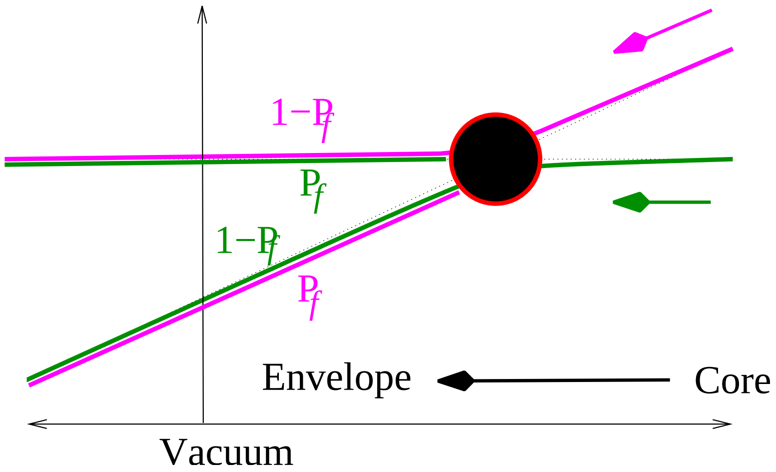


Inverted mass hierarchy



- H resonance: $(\Delta m^2_{\rm atm}, \theta_{13})$, $\rho \sim 10^3$ g/cc
  In ν channel for normal hierarchy, $\bar{\nu}$ channel for inverted hierarchy
- L resonance: $(\Delta m^2_{\odot}, \theta_{\odot})$, $\rho \sim 10$ g/cc
  Always in ν channel
- Δm^2 hierarchy $\Rightarrow$ Independent dynamics at resonances

Conversion probability at resonance



$$P_f \approx exp\left(-\frac{\pi}{2}\gamma\right) \quad , \quad \gamma \equiv \frac{\Delta m^2}{2E}\frac{\sin^2 2\theta}{\cos 2\theta}\left(\frac{1}{n_e}\frac{dn_e}{dr}\right)^{-1}$$

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

Landau’1932, Zener’1932

- L resonance always adiabatic
- H resonance adiabatic for $|U_{e3}|^2 \gtrsim 10^{-3}$,
  non-adiabatic for $|U_{e3}|^2 \lesssim 10^{-5}$

Fluxes arriving at the Earth

Mixture of initial fluxes:

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

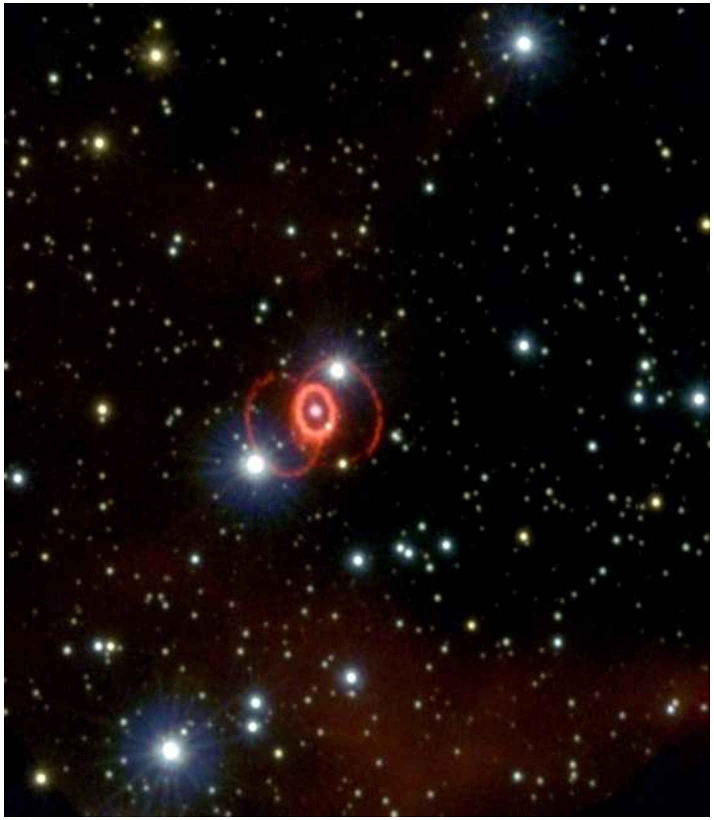
Survival probabilities in different scenarios:

Case	Hierarchy	$\sin^2\Theta_{13}$	p	$\bar{p}$
A	Normal	large	0	$\cos^2\Theta_\odot$
B	Inverted	large	$\sin^2\Theta_\odot$	0
C	Any	small	$\sin^2\Theta_\odot$	$\cos^2\Theta_\odot$

- "Small": $\sin^2\Theta_{13} \lesssim 10^{-3}$, "Large": $\sin^2\Theta_{13} \gtrsim 10^{-3}$.

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

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

J. Arafune, J. Bahcall, V. Barger, M. Fukugita, B. Jegerlehner, M Kachelrieß, C. Lunardini, D. Marfatia, H. Minakata, F. Neubig, D. Nötzold, H. Nunokawa, G. G. Raffelt, K. Shiraishi, A. Smirnov, D. Spergel, A. Strumia, H. Suzuki, R. Tomàs, J. V. F. Valle, B. Wood, T. Yanagida, M. Yoshimura, *et al*

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

Distinguishing neutrino mixing scenarios

The task at hand

Measure the spectra, determine the mixing scenario.

A. Bandyopadhyay, S. Choubey, I. Gil-Botella, S. Goswami, M. Kachelrieß,
K. Kar, C. Lunardini, H. Minakata, H. Nunokawa, G. Raffelt, A. Rubbia,
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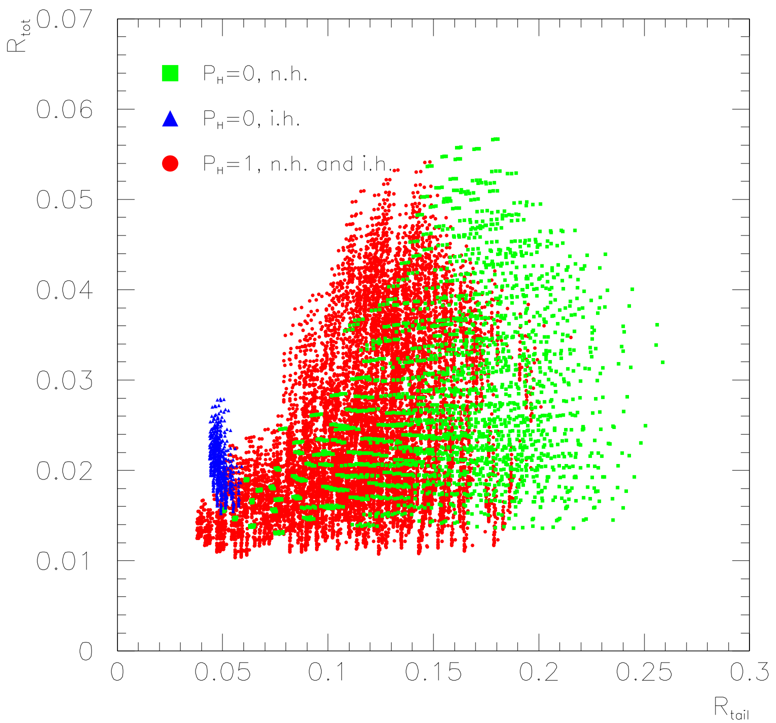
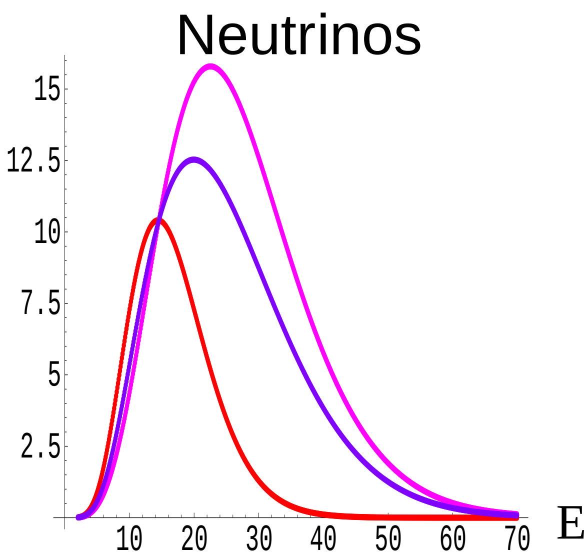


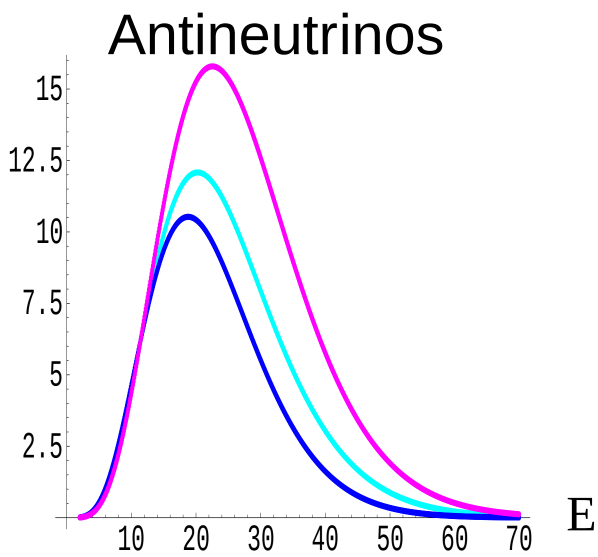
- Poorly known initial spectra
- Only final $\bar{\nu}_e$ spectrum cleanly available.
- Difficult to find a "clean" observable, i.e. one independent of some assumptions about the initial spectra

C. Lunardini, A. Smirnov, JCAP 0306:009 (2003)

Exploiting Earth matter effects



(ν_e, ν_x, mixed ν)



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

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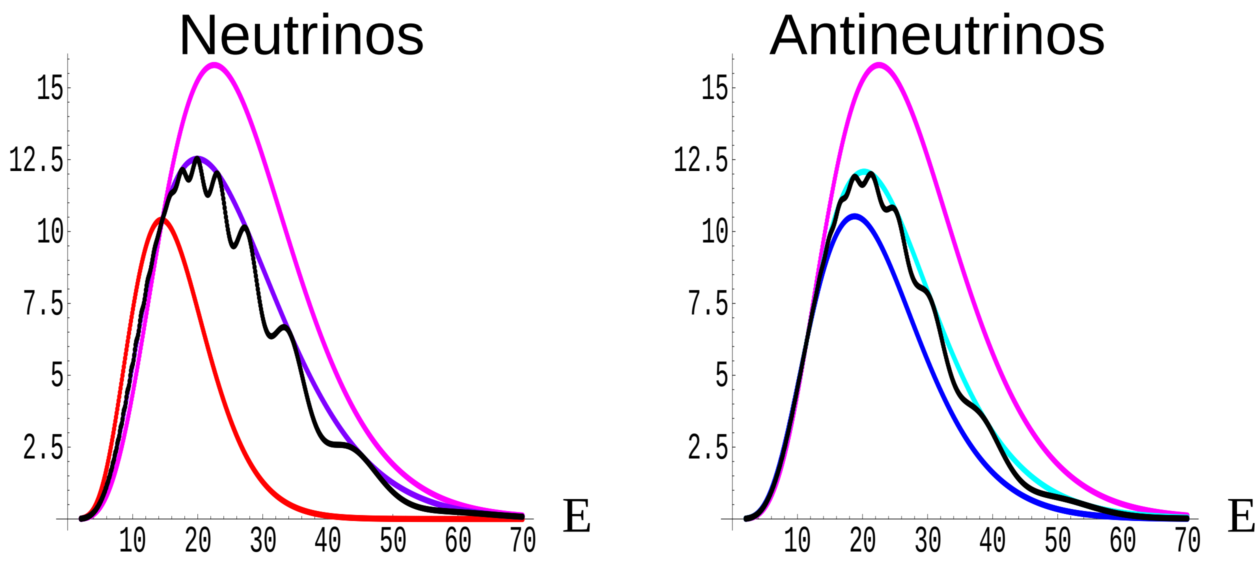
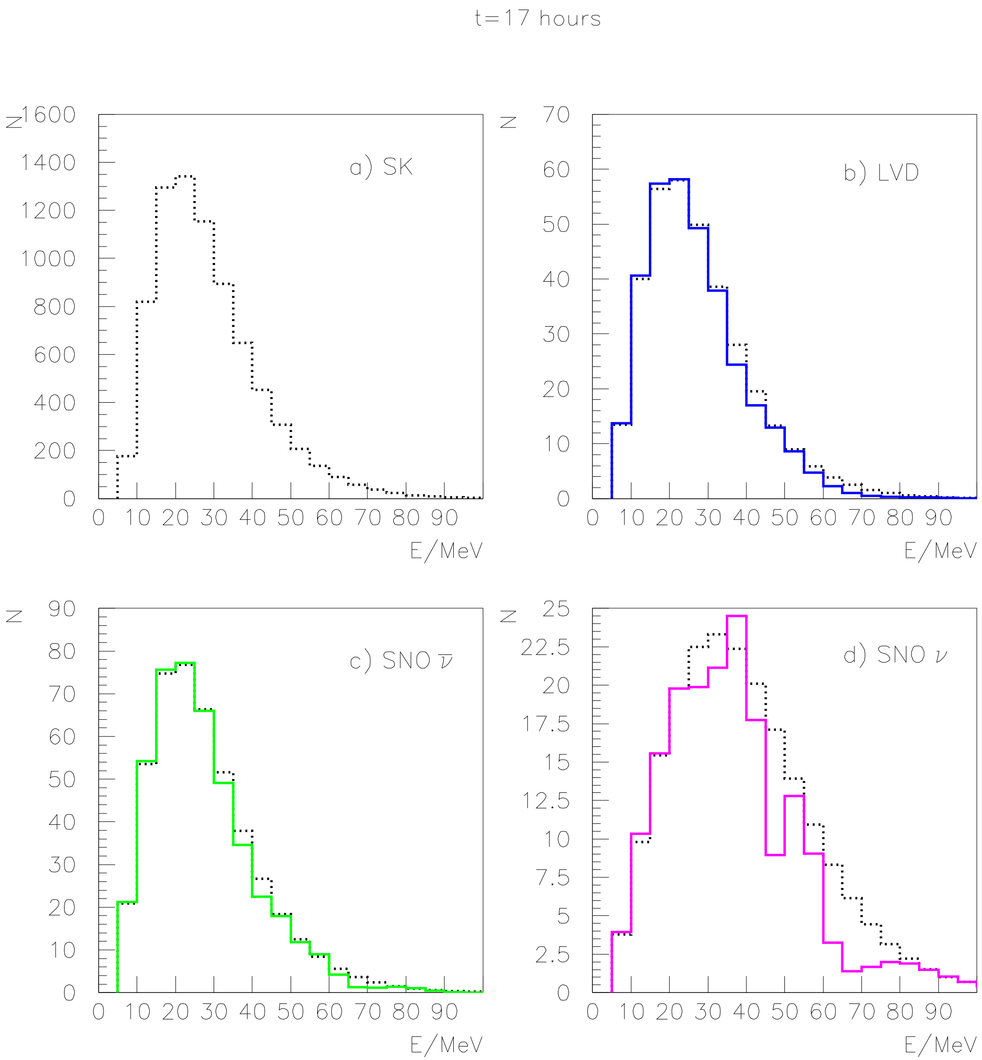


(ν_e, ν_x, mixed ν)   ($\bar{\nu}_e$, $\bar{\nu}_x$, mixed $\bar{\nu}$)

- Total number of events (in general) decreases
  - Compare signals at two detectors
- "Earth effect" oscillations are introduced
  - Scenarios B, C for ν_e, scenarios A, C for $\bar{\nu}_e$

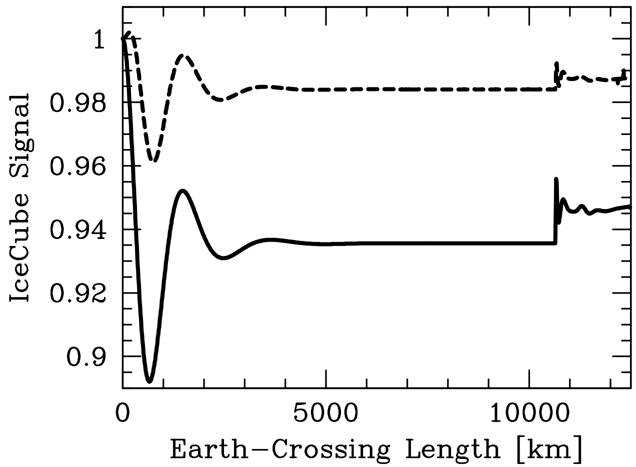
Comparing spectra at multiple detectors



C. Lunardini and A. Smirnov, NPB616:307 (2001)

IceCube as a co-detector with SK/HK

- IceCube primarily meant for individual neutrinos with energy $\gtrsim 150$ GeV
- For a SN burst at 10 kpc, the luminosity can be determined to a statistical accuracy of $\sim 0.25\%$ over and above the statistical background fluctuations
- 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)

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

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

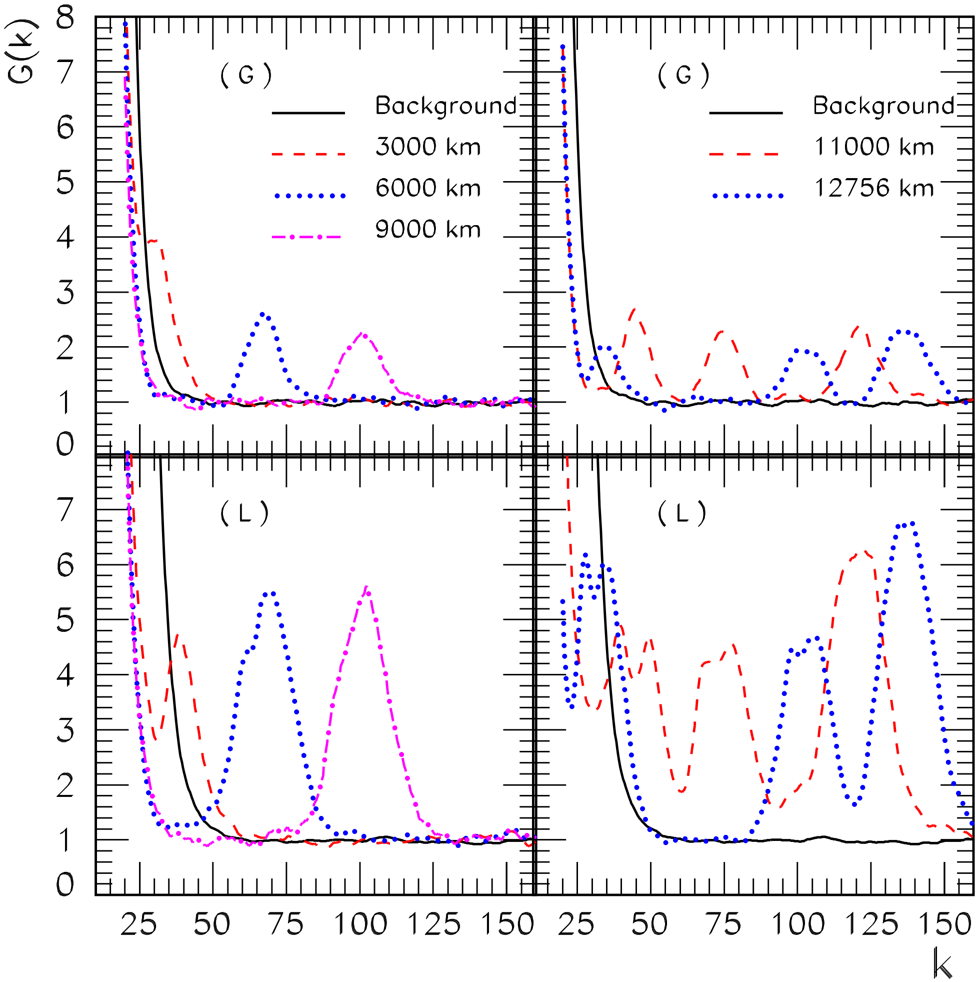
Oscillation frequency: $k_\oplus \equiv 2\overline{\Delta m^2_\oplus} L$

- 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
- Fourier transform: peak in the power spectrum
  $G_N(k) = \frac{1}{N} \left|\sum_{events} e^{iky}\right|^2$

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

At a scintillation detector

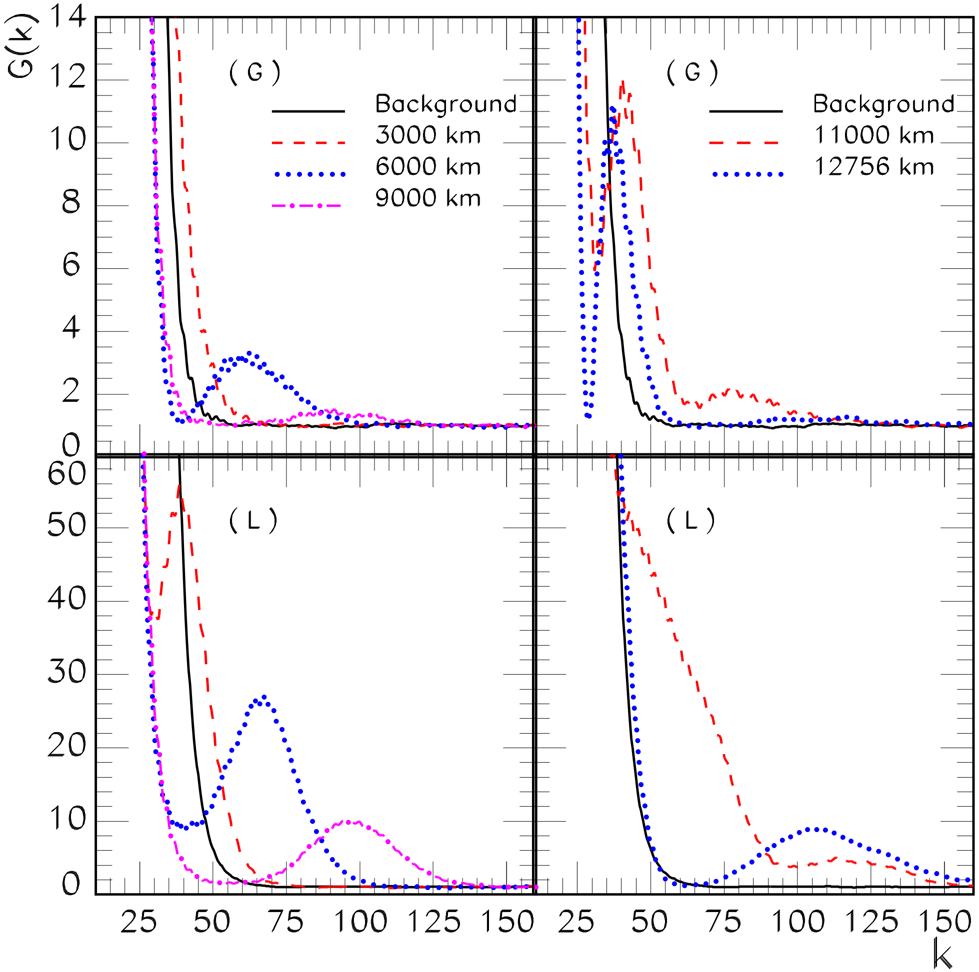
- Passage through the Earth core gives rise to extra peaks.
- Model independence of peak positions:



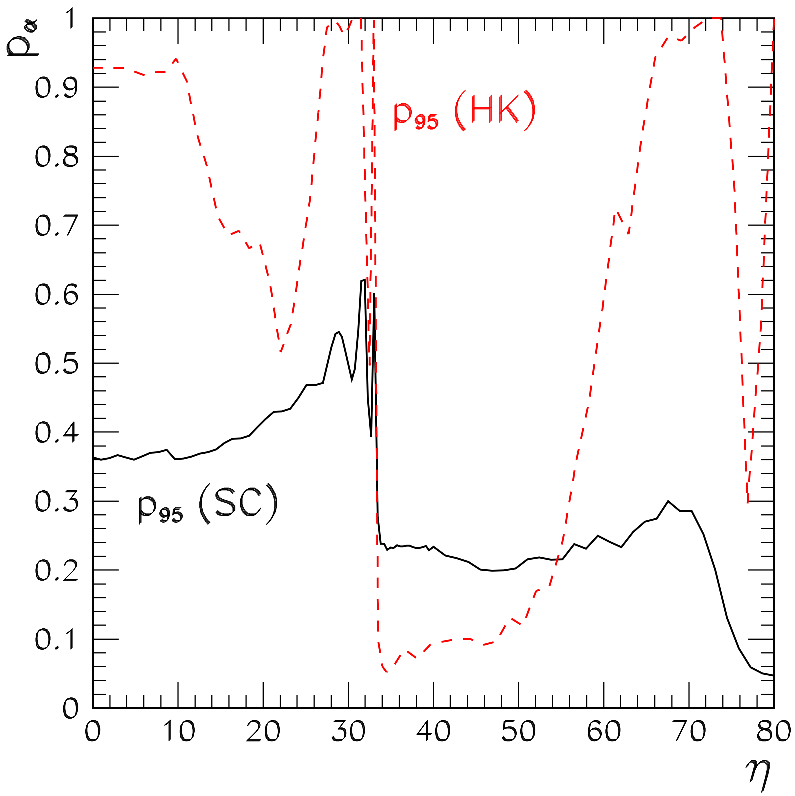
AD, M. Kachelrieß, G. Raffelt, R. Tomàs, JCAP 0401:004 (2004)

At a water Cherenkov detector

- High-k suppression:



Efficiencies of detectors



- High-k suppression affects the efficiency of HK for $35° < \eta < 55°$. (η: nadir angle)
- Large number of events compensates for poorer energy resolution

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

- Observation of a Fourier peak in $\bar{\nu}_e \Rightarrow$
  Eliminate scenario B independently of SN models !!!

Neutrinos for SN astrophysics

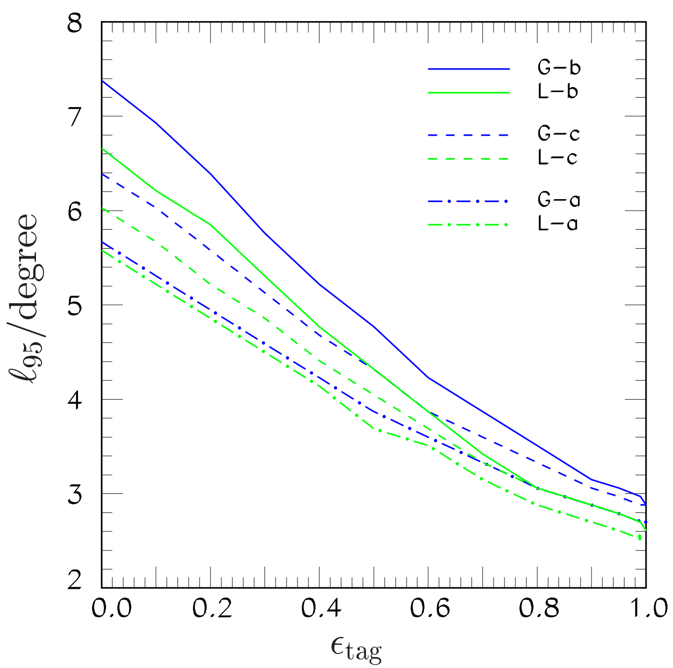
- Pointing to the SN in advance
- Learning about the shock wave

Pointing to the SN in advance (*at SK*)

J. Beacom and P. Vogel, PRD60:033007 (1999)

- Needed if no optical observation
- $\bar{\nu}_e p \to n e^+$: nearly isotropic background
- $\nu e^- \to \nu e^-$: forward-peaked “signal”
- Background-to-signal ratio: $N_B/N_S \approx 30\text{–}50$
- Decrease N_B/N_S: neutron tagging with Gd

1



Pointing accuracy improved 2–3 times using Gd

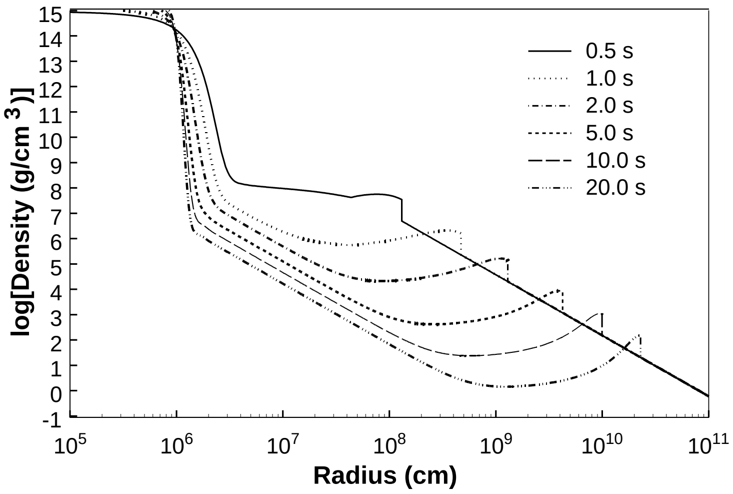
R. Tomàs, D. Semikoz, G. Raffelt,
M. Kachelrieß, AD, PRD 68, 093013 (2003).

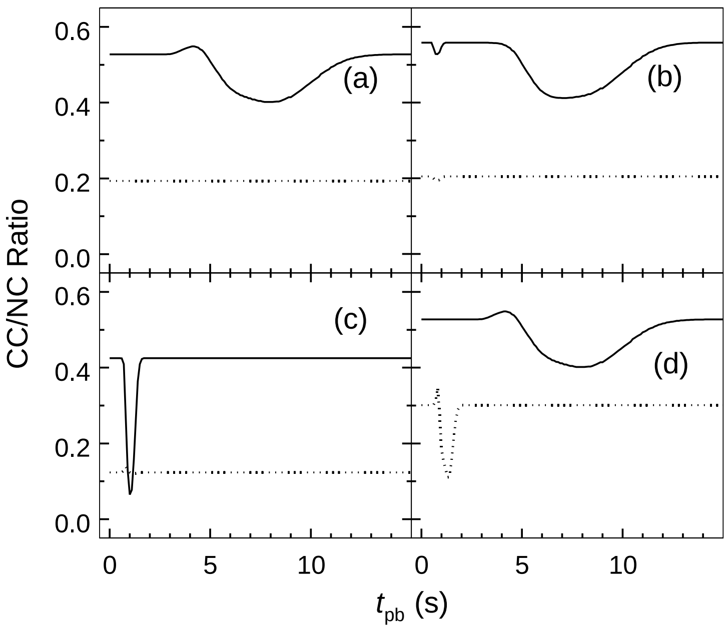
GADZOOKS

(Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!)

J. F. Beacom and M. R. Vagins,
hep-ph/0309300

Observing the shock wave "in neutrinos"

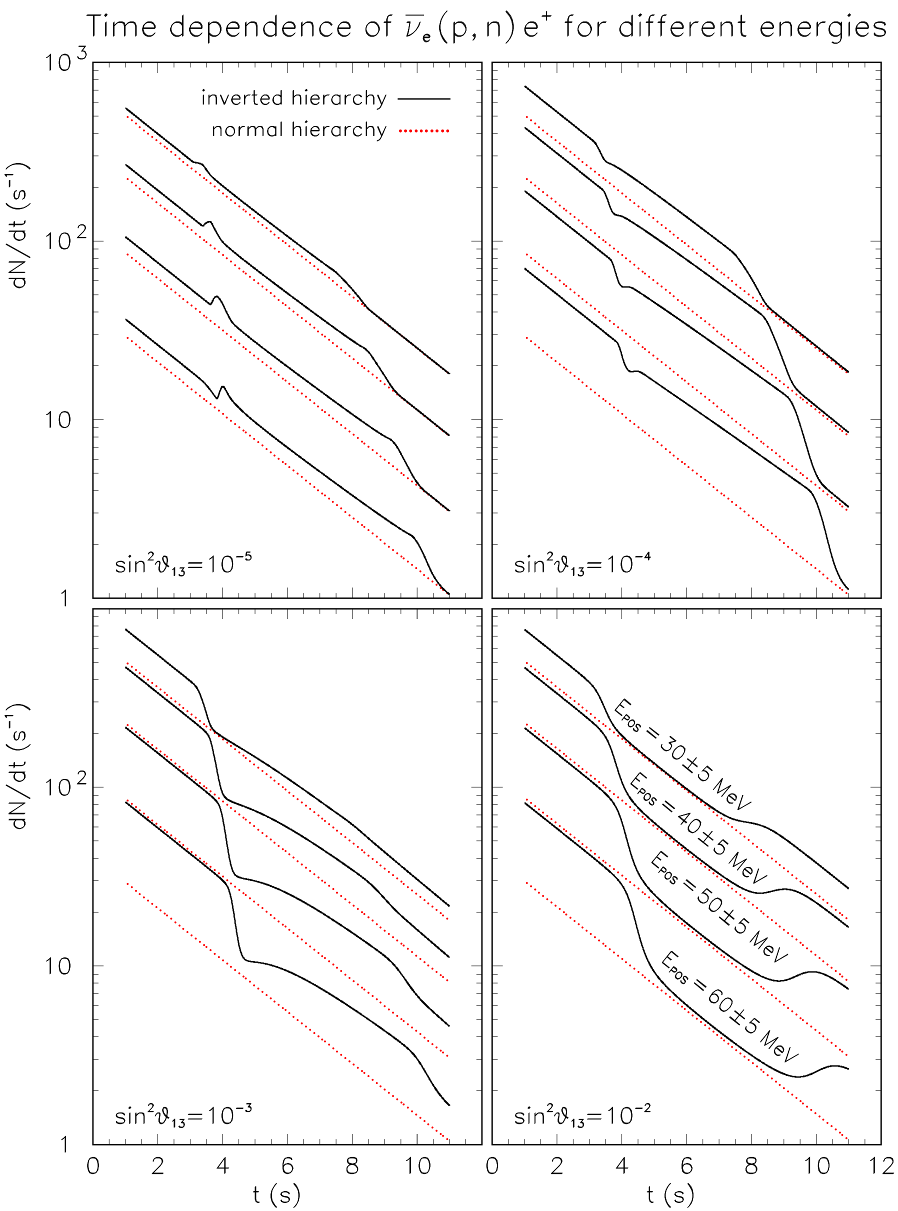




- When shock wave passes through a resonance region, adiabatic resonances may become non-adiabatic for some time
  scenario A → scenario C
  scenario B → scenario C
- May cause sharp changes in the final spectra even if the primary spectra are unchanged / smoothly changing

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

Detection of the shock wave in the mantle

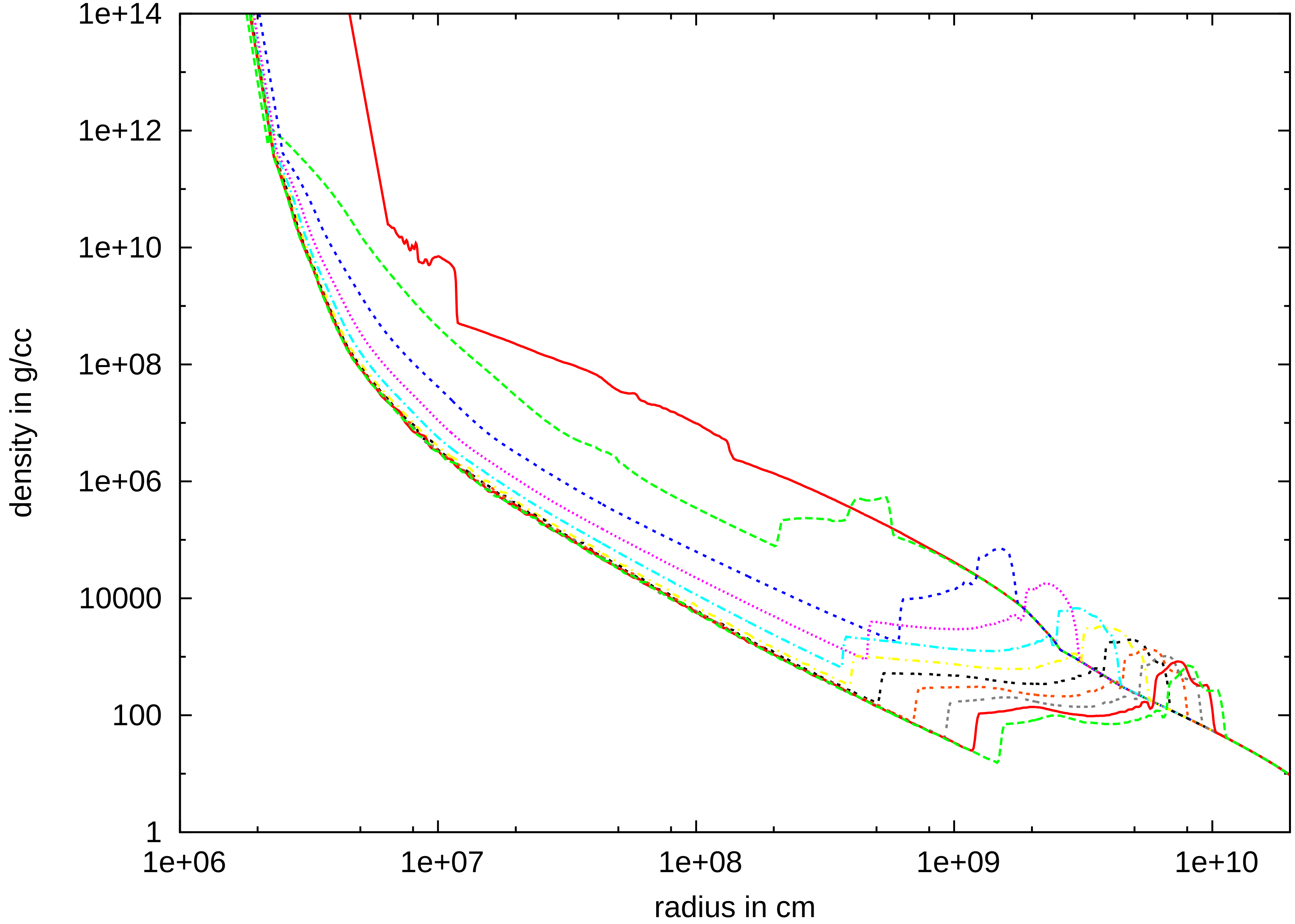


Sudden jumps in the neutrino spectra ⇒

- neutrino mixing scenario
- Time the shock wave passed through the region $\rho \sim 10^3$ g/cc.

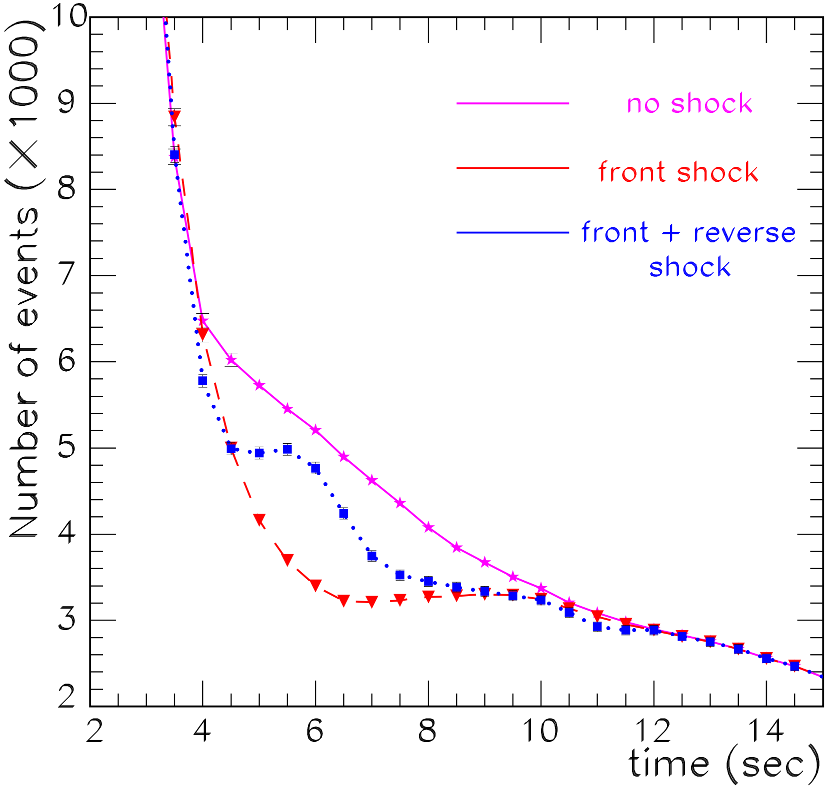
G. L. Fogli, E. Lisi, D. Montanino and A. Mirizzi, PRD 68, 033005 (2003)

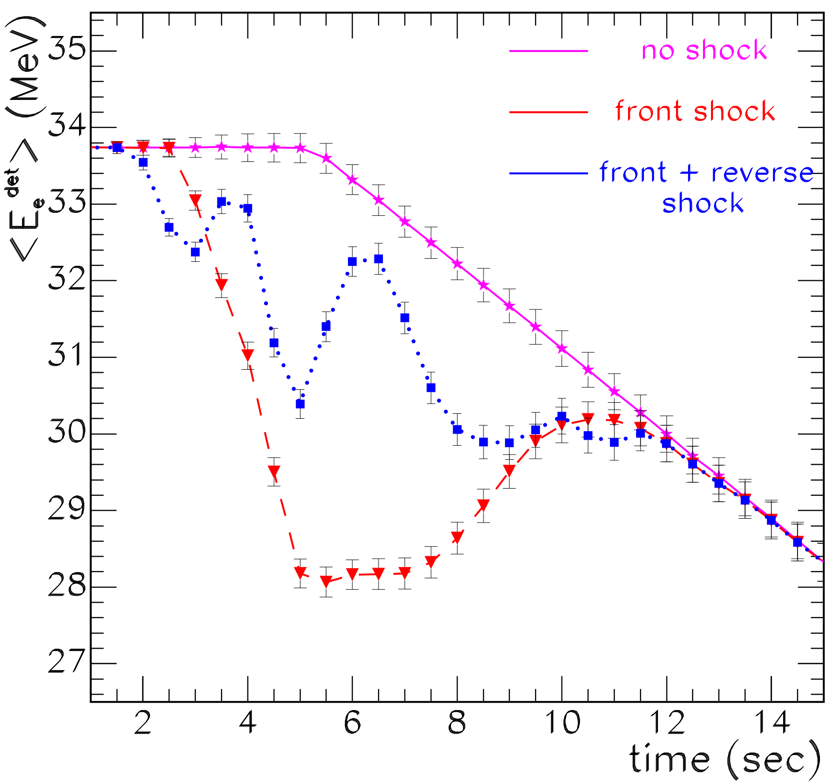
Reverse shock



H.-T. Janka, L. Scheck

Signatures of a reverse shock (*at HK*)





- Only for scenario B !!

AD, H.-T. Janka, M. Kachelrieß, G. Raffelt, L. Scheck, R. Tomàs

Summary

- Primary neutrino spectra: flavor and model dependence
- Role of neutrinos in SN explosion: important, but more ingradients needed for a successful explosion
- Flavor conversions inside SN sensitive to normal vs. inverted hierarchy and “small” vs. “large” mixing angle θ_{13}.
- A positive identification of Earth effects on antineutrinos: a model independent way of ruling out inverted hierarchy and large θ_{13}.
  - Comparison of signals at multiple detectors (HK & IceCube)
  - Identifying modulations in a single detector (energy resolution vs. size)
- Advance SN pointing accuracy with neutrinos less than 10° Improved 2–3 times using Gd to tag neutrons.
- Observing the shock wave in neutrinos $\Rightarrow$ features of shock wave and neutrino mixing scenarios

Things to do while waiting for a SN

- Better theoretical understanding of neutrino transport inside the SN and the explosion mechanism
- More accurate measurements of the neutrino mixing parameters
- Tuning of long-term detectors to observe SN neutrino signals

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> A rare event is a lifetime opportunity – Anon