Galactic Supernova for neutrino mixing and SN astrophysics

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Mumbai

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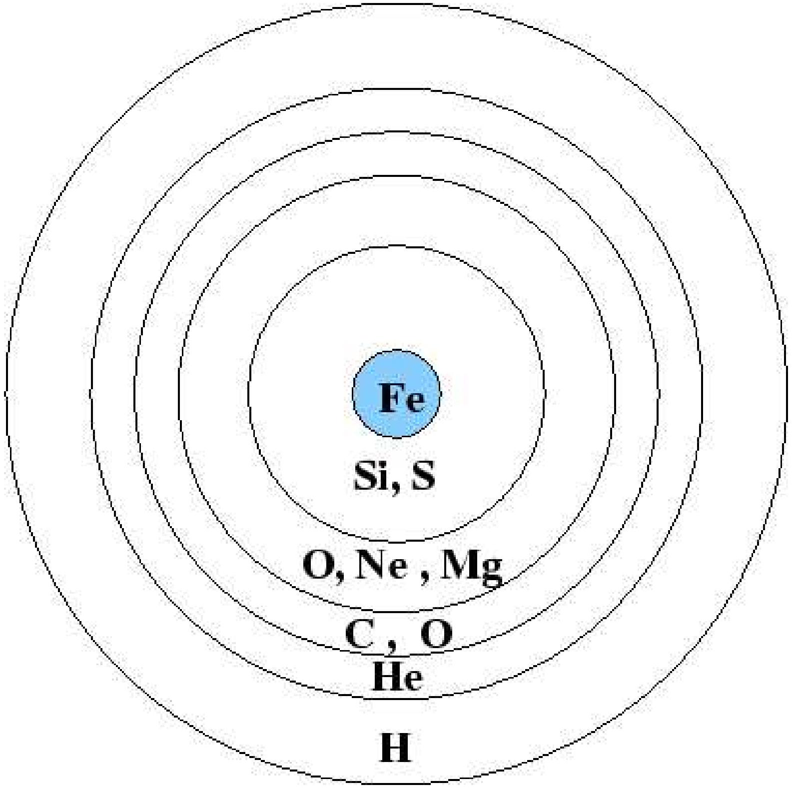
Why study a rare event

(¿¿ Galactic SN: once in a few decades ??)

- For neutrino mixing:
  - Identifying normal / inverted mass hierarchy
  - Probing extremely low values of θ_{13}
- For SN astrophysics:
  - Pointing to the SN in advance
  - Tracking the shock wave propagation inside SN
- For being prepared to observe relevant signals:
  - Water Cherenkov / Ice Cherenkov
  - Carbon-based Scintillator
  - Liquid Ar
- For long-term future:
  - A guide for design parameters of future long baseline experiments [superbeams / neutrino factories]

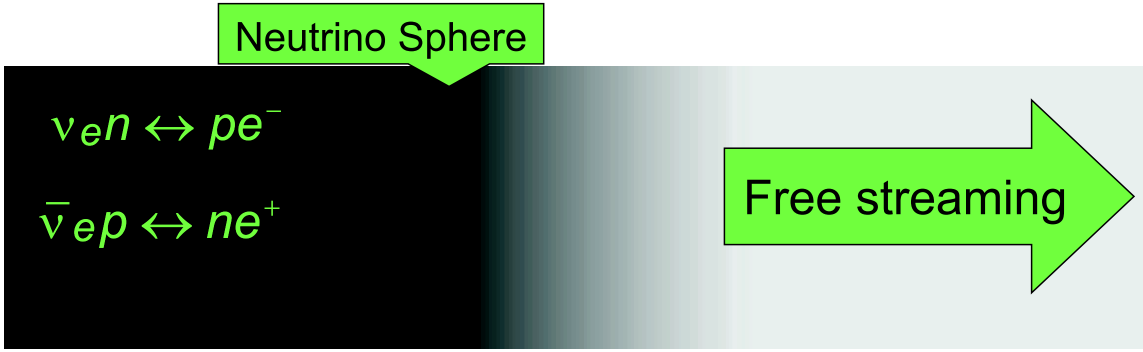
A Type II supernova

“Onion-shell” structure:



Trapped neutrinos before the collapse

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

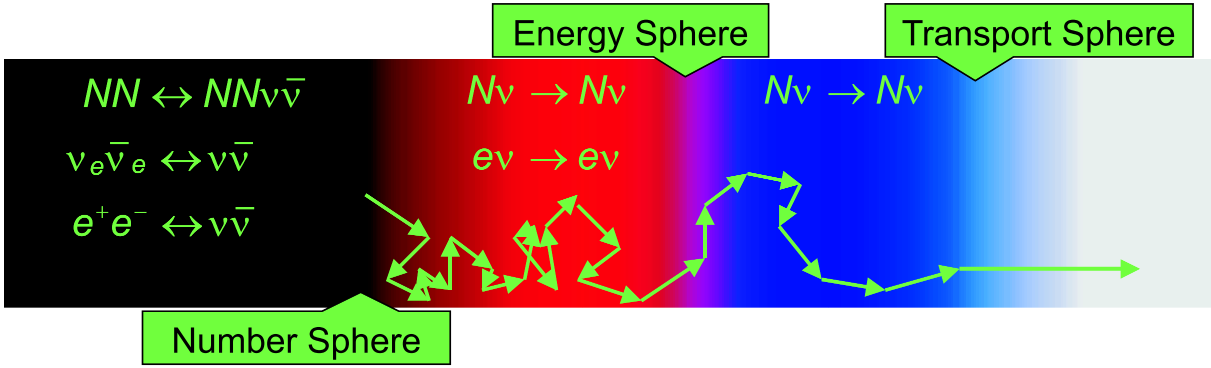


Neutrino Sphere

$\nu_e n \leftrightarrow p e^-$

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

Free streaming



Energy Sphere

Transport Sphere

$NN \leftrightarrow NN\nu\bar{\nu}$

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

$e^+e^- \leftrightarrow \nu\bar{\nu}$

$N\nu \to N\nu$

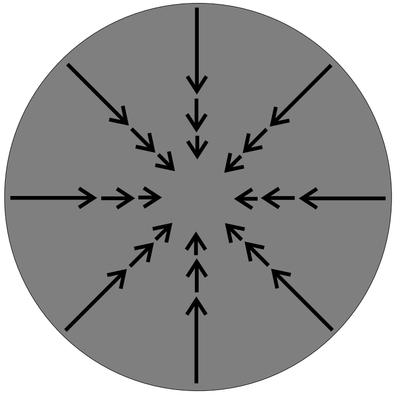
$e\nu \to e\nu$

$N\nu \to N\nu$

Number Sphere

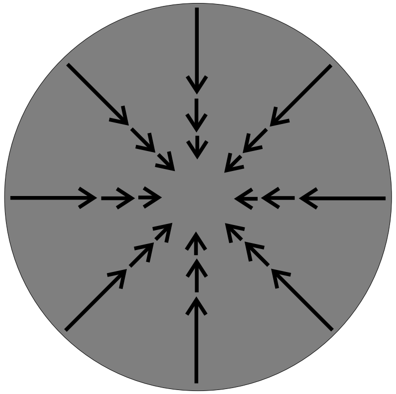
The core collapse

- Gravitational core collapse

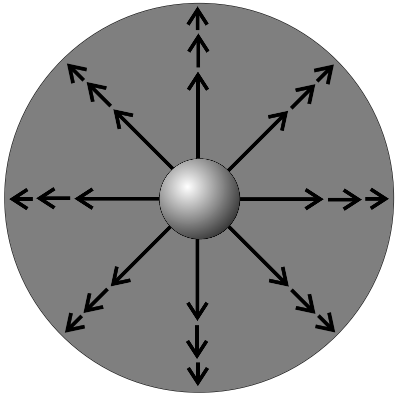


The core collapse

- Gravitational core collapse



- Generation of a shock wave



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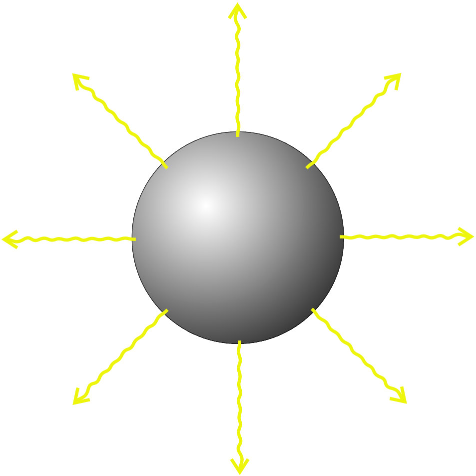
- Cooling through neutrino emission: $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$
  Duration: About 10 sec
  Emission of 99% of the SN energy in neutrinos



Can be used for “pointing” to the SN
in advance. (“Early warning”)

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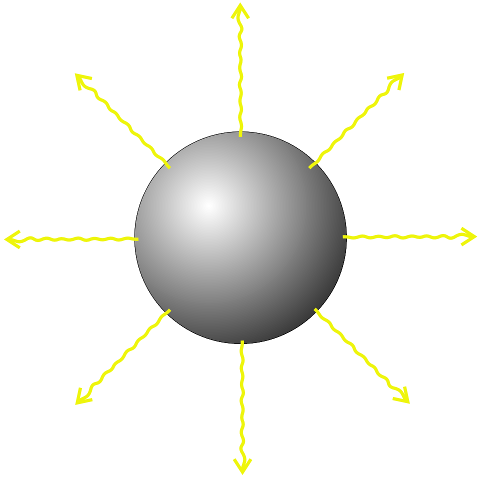


Can be used for “pointing” to the SN
in advance. (“Early warning”)

- ¿¿¿ Explosion ???

Initial neutrino spectra

Neutrino fluxes:

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

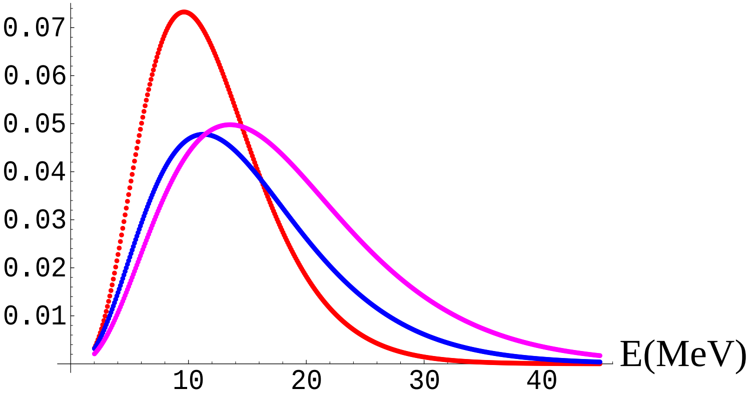
E_0, α: in general time dependent

Known properties of the spectra:

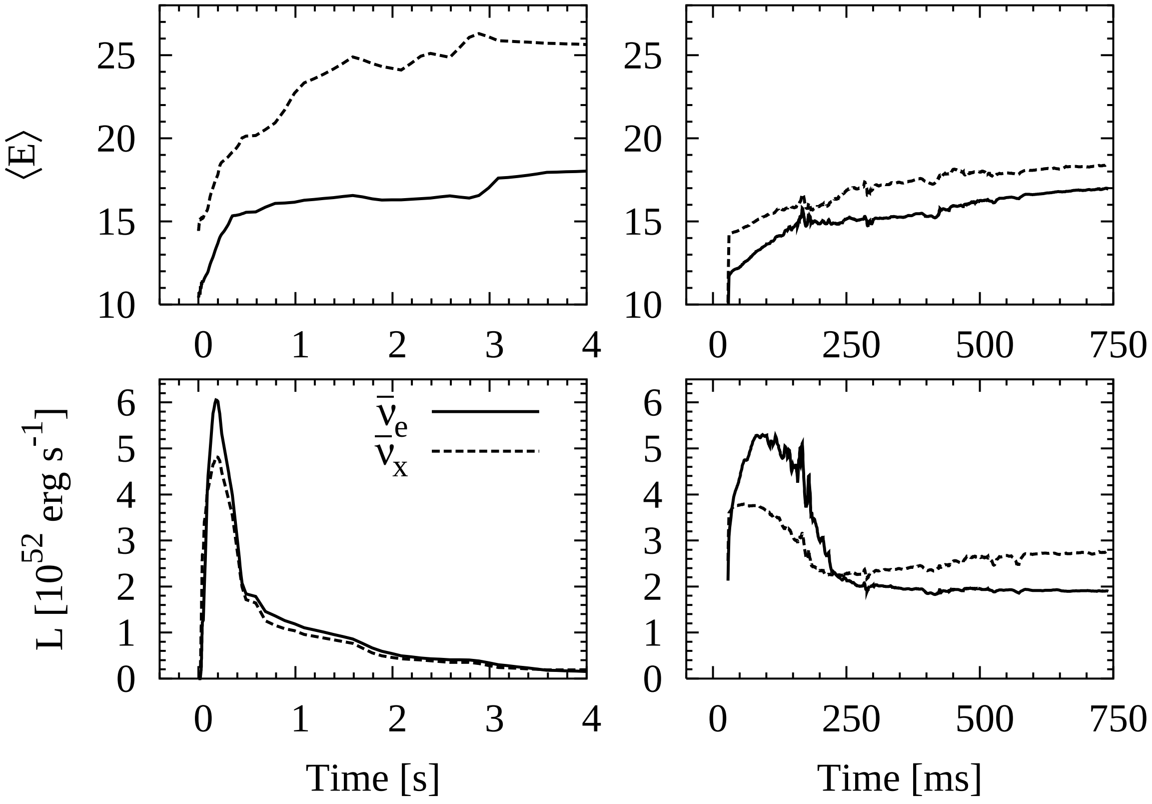
- Energy hierarchy: $E_0(\nu_e) < E_0(\bar{\nu}_e) < E_0(\nu_x)$
- Spectral pinching: $\alpha_{\nu_i} > 2$

$E_0(\nu_e) \approx 10$–12 MeV
$E_0(\bar{\nu}_e) \approx 13$–$16$ MeV
$E_0(\nu_x) \approx 15$–25 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



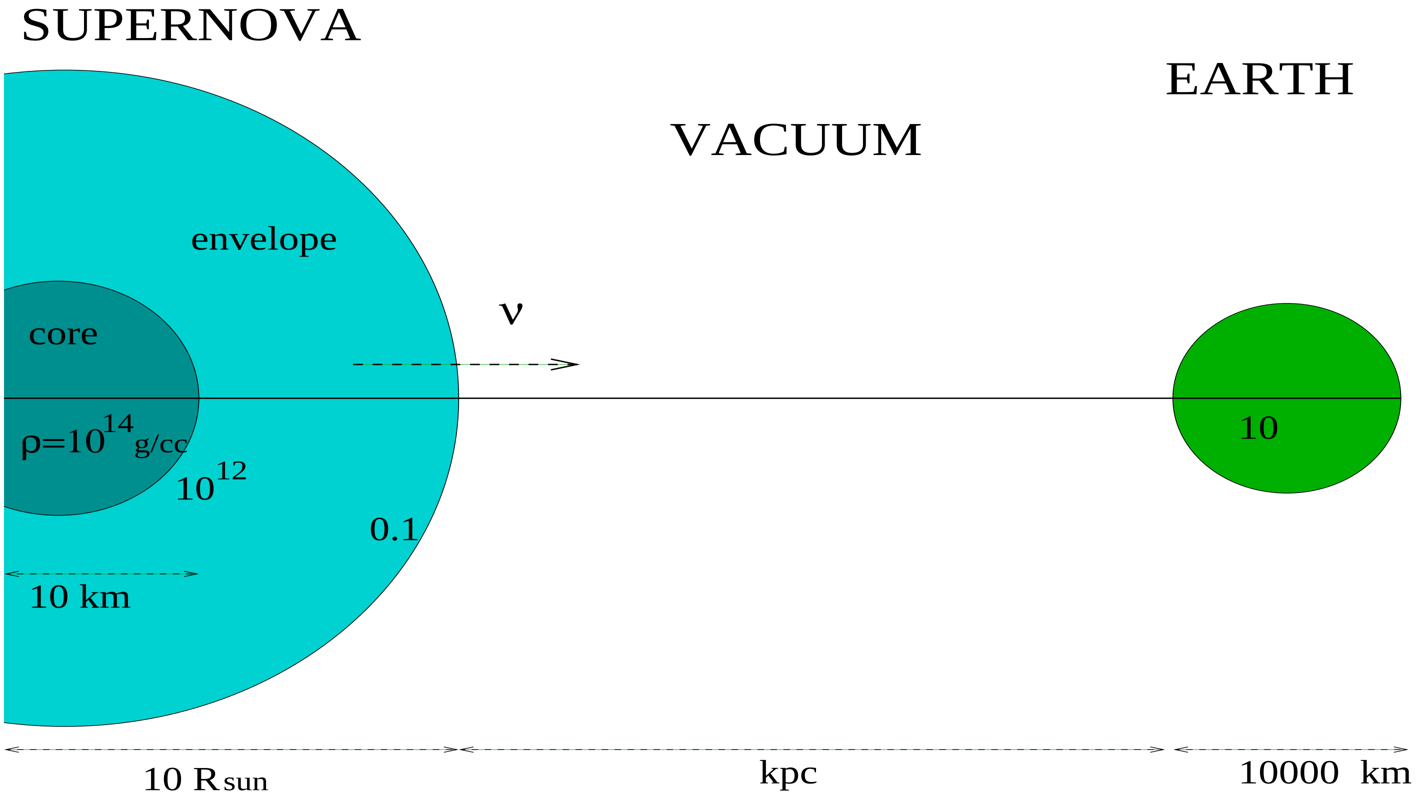
solid line: $\bar{\nu}_e$
dotted line: $\bar{\nu}_x$

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)

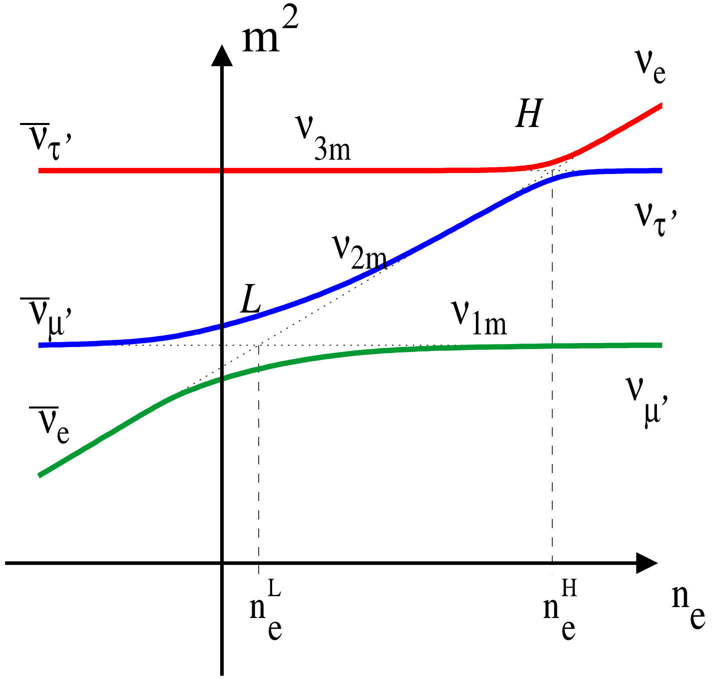
Propagation through matter



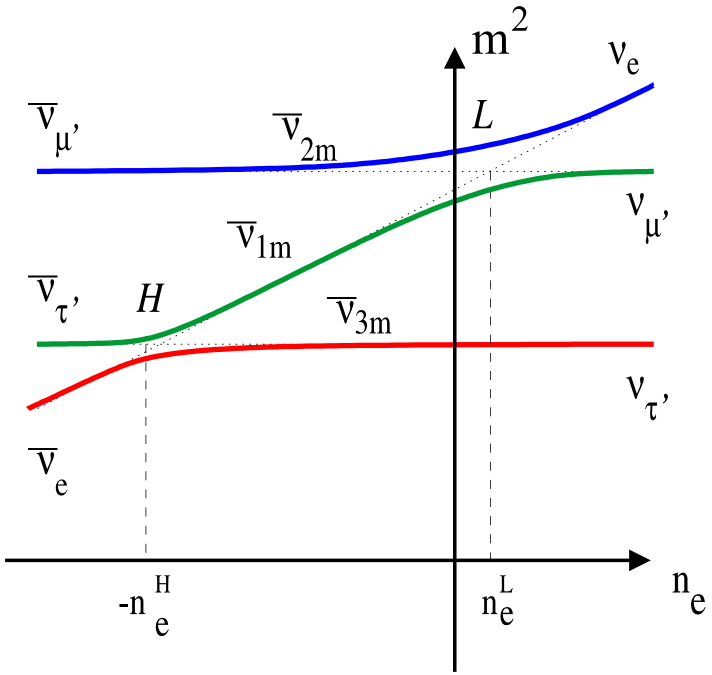
- Matter effects on neutrino mixing crucial
- Flavor conversions at resonances / level crossings

Level crossings during propagation

Normal mass hierarchy

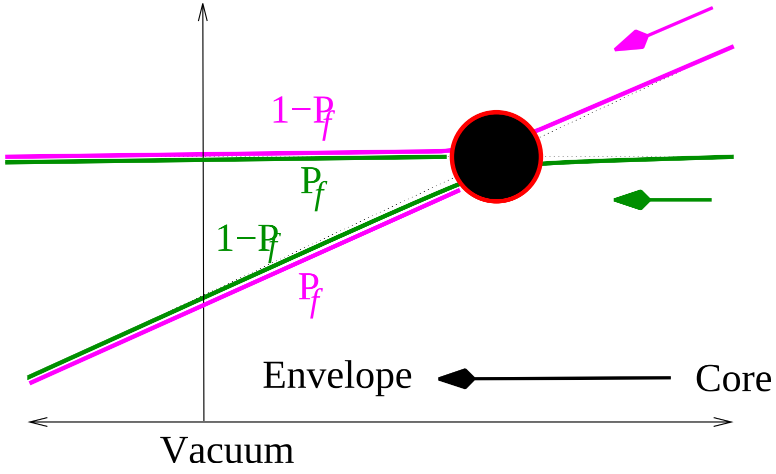


Inverted mass hierarchy



- 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 $|U_{e3}|^2 \lesssim 10^{-5}$

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

Fluxes arriving at the Earth

Mixture of initial fluxes:

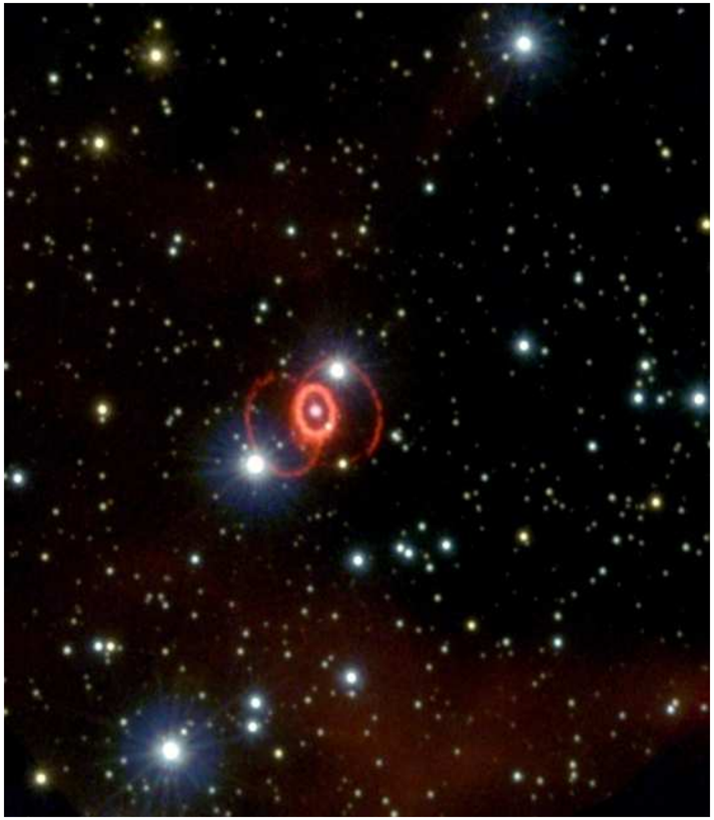
$$\begin{aligned} F_{\nu_e} &= p F^0_{\nu_e} + (1-p) F^0_{\nu_x} \ , \\ F_{\bar{\nu}_e} &= \bar{p} F^0_{\bar{\nu}_e} + (1-\bar{p}) F^0_{\nu_x} \ , \\ 4F_{\nu_x} &= (1-p) F^0_{\nu_e} + (1-\bar{p}) F^0_{\bar{\nu}_e} + (2+p+\bar{p}) F^0_{\nu_x} \ . \end{aligned}$$

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”: $\sin^2\Theta_{13} \lesssim 10^{-5}$, “Large”: $\sin^2\Theta_{13} \gtrsim 10^{-3}$.
- Sensitivity to $\sin^2\Theta_{13}$ an order of magnitude better than current reactor experiments !

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:

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

Some useful reactions at other detectors:

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

Identifying
neutrino mixing scenario

A ?? B ?? C ??

The task at hand

Measure the spectra, determine the mixing scenario.

A. Bandyopadhyay, AD, S. Choubey, G. Dutta, I. Gil-Botella, S. Goswami, D. Indumathi, M. Kachelrieß, K. Kar, C. Lunardini, H. Minakata, M. V. N. Murthy, H. Nunokawa, G. Raffelt, G. Rajasekaran, A. Rubbia, K. Sato, A. Smirnov, K. Takahashi, R. Tomàs, J. Valle, *et al*

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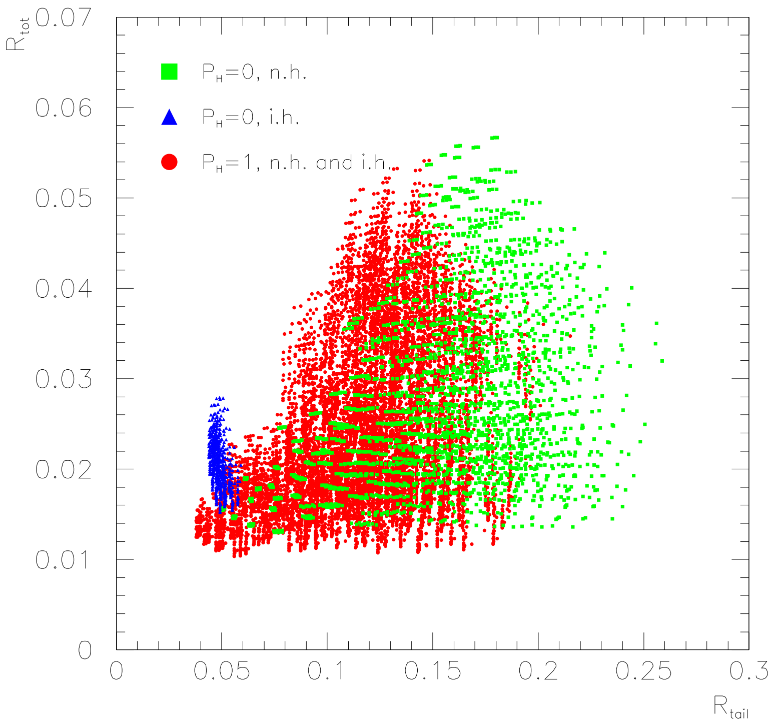


- Poorly known initial spectra
- Only final $\bar{\nu}_e$ spectrum cleanly available (till we have liquid Ar)
- Difficult to find a “clean” observable, i.e. one independent of some assumptions about the initial spectra

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

Some possible observables

- During neutronization burst: $R^B \equiv N^{CC}/N^{NC}$
  Case A $\Rightarrow R^B/R_0^B \approx |U_{e3}|^2 \leq 0.05$
- Broadening of spectra:
  pinched $\rightarrow$ antipinched, i.e. $\alpha > 2 \rightarrow \alpha < 2$
- Pinching parameter $3\langle E^2\rangle/4\langle E\rangle^2$:
  Information about the spectrum around the peak
- Tail fraction:

$$f_{tail} = \frac{N(E > E_{\rm tail})}{N(E > E_{\rm th})}$$

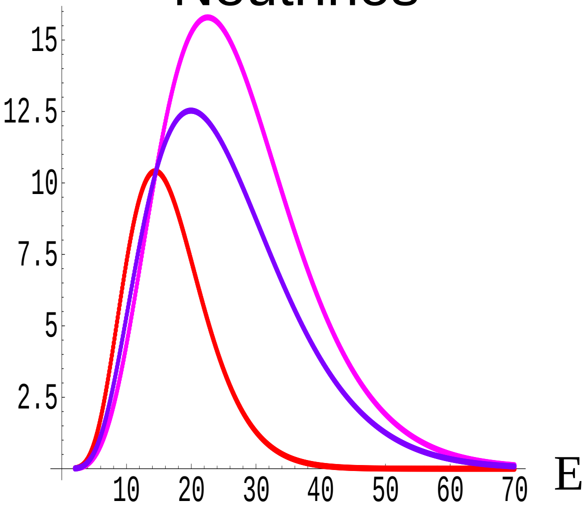
Information about the high-energy part of the spectrum

Difficult to find a “clean” observable, i.e. one independent of some assumptions about the initial spectra.

M. Kachelrieß, C. Lunardini, H. Minakata, H. Nunokawa, G. Raffelt,
K. Sato, A. Smirnov, K. Takahashi, R. Tomàs, J. Valle, *et al*

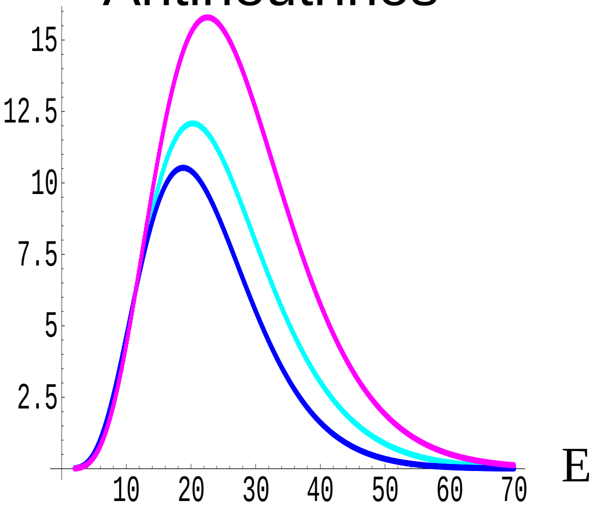
Exploiting Earth matter effects

Neutrinos



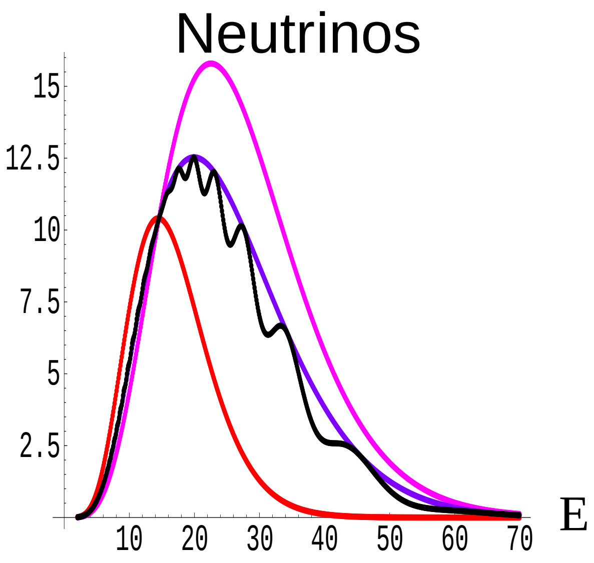
$(\nu_e, \nu_x,$ mixed $\nu)$

Antineutrinos

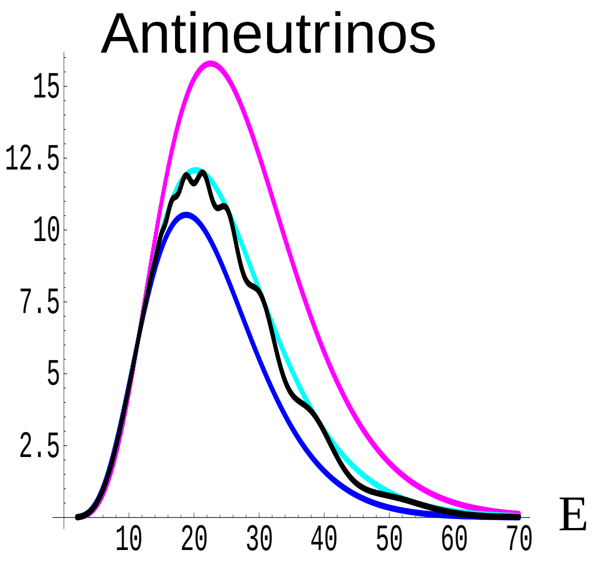


$(\bar{\nu}_e, \bar{\nu}_x,$ mixed $\bar{\nu})$

Exploiting Earth matter effects



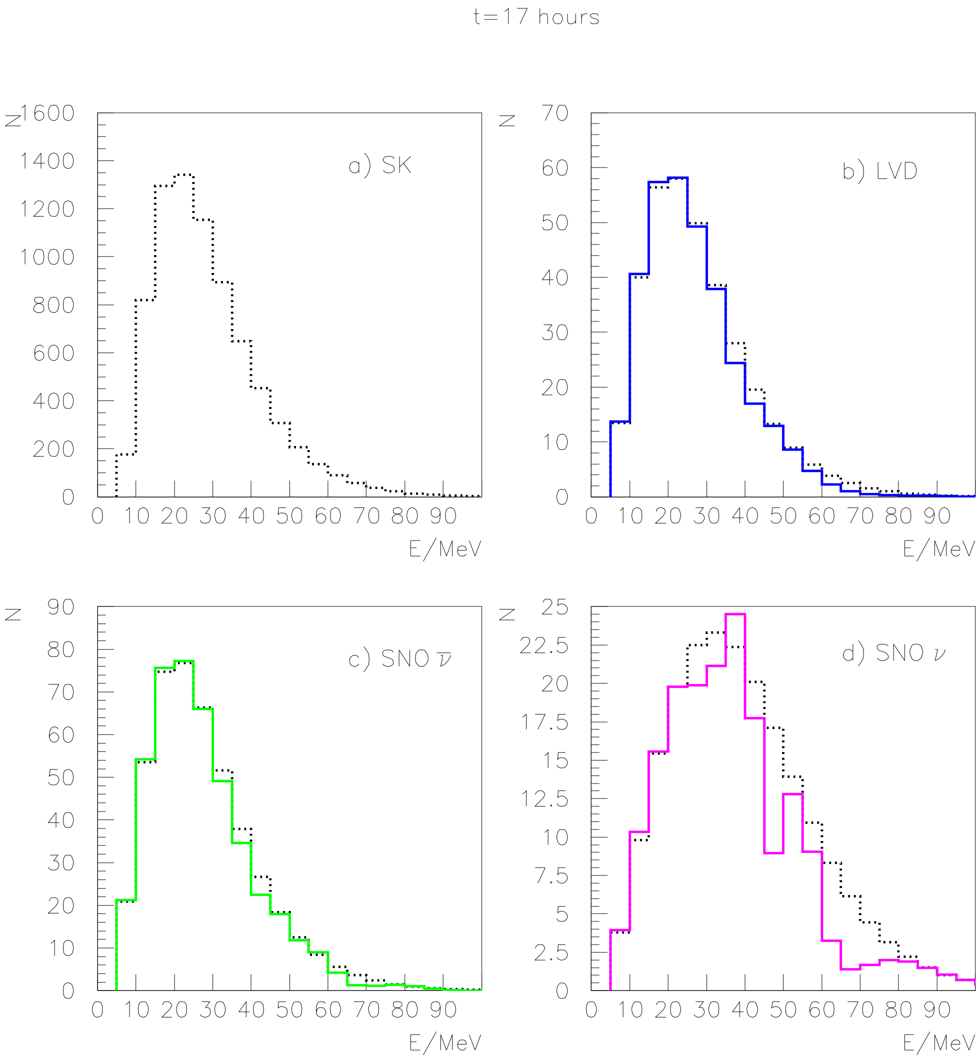
(ν_e, ν_x, mixed ν)



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

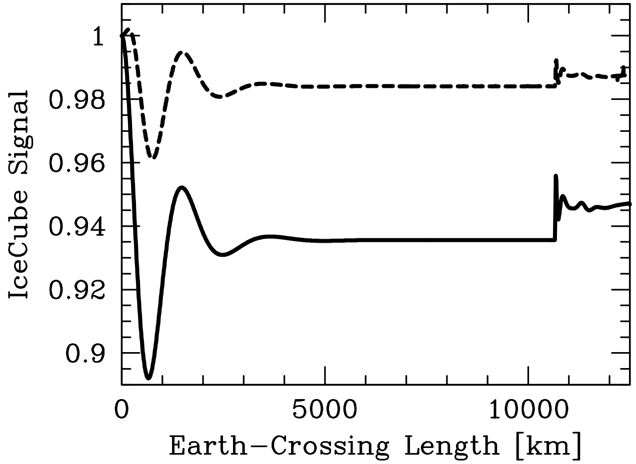
Comparing spectra at multiple detectors



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

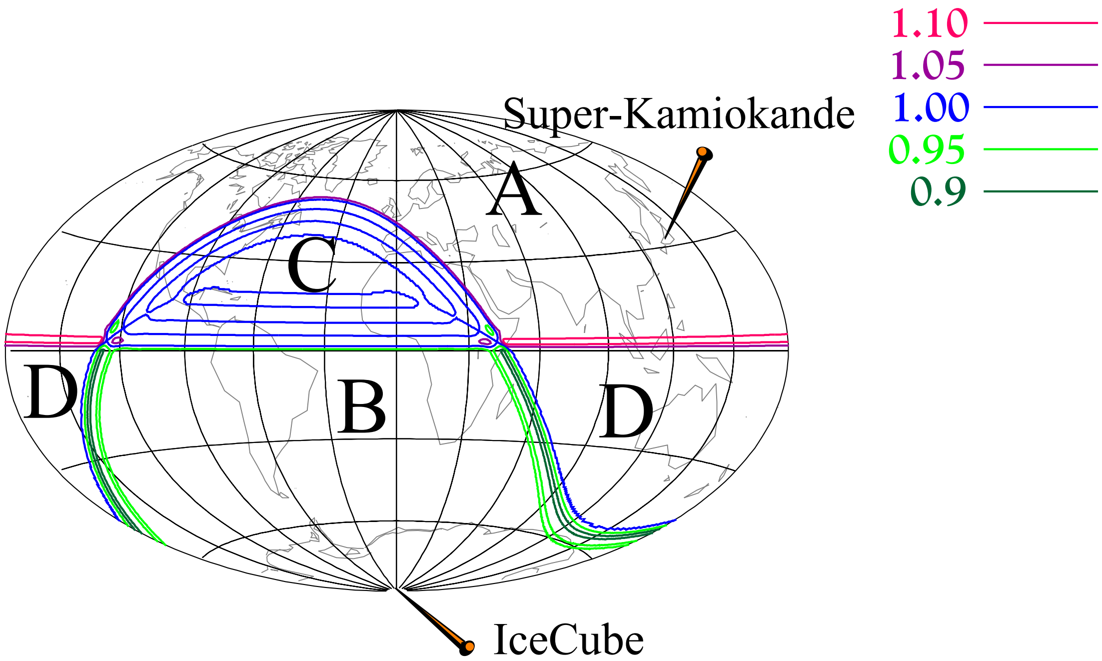
IceCube as a co-detector with SK/HK

- IceCube primarily meant for 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

Useful SN locations for SK-IC comparison

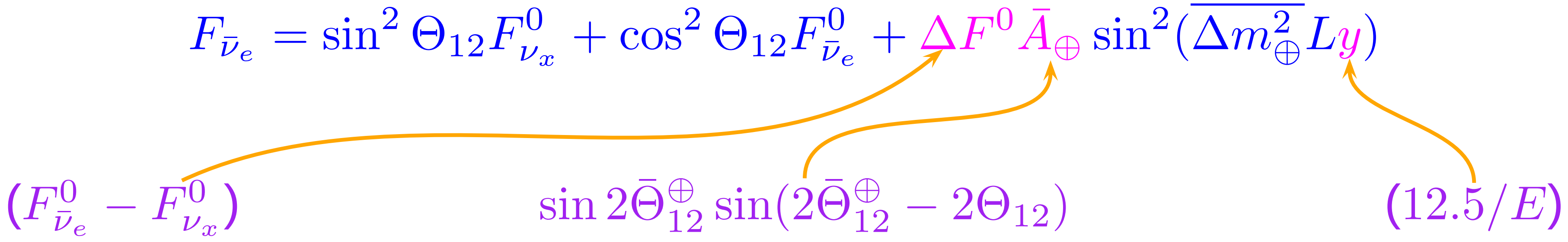


Earth effects detectable in regions (A) and (B)

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

At a single detector

(Identifying Earth oscillation frequency)



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

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

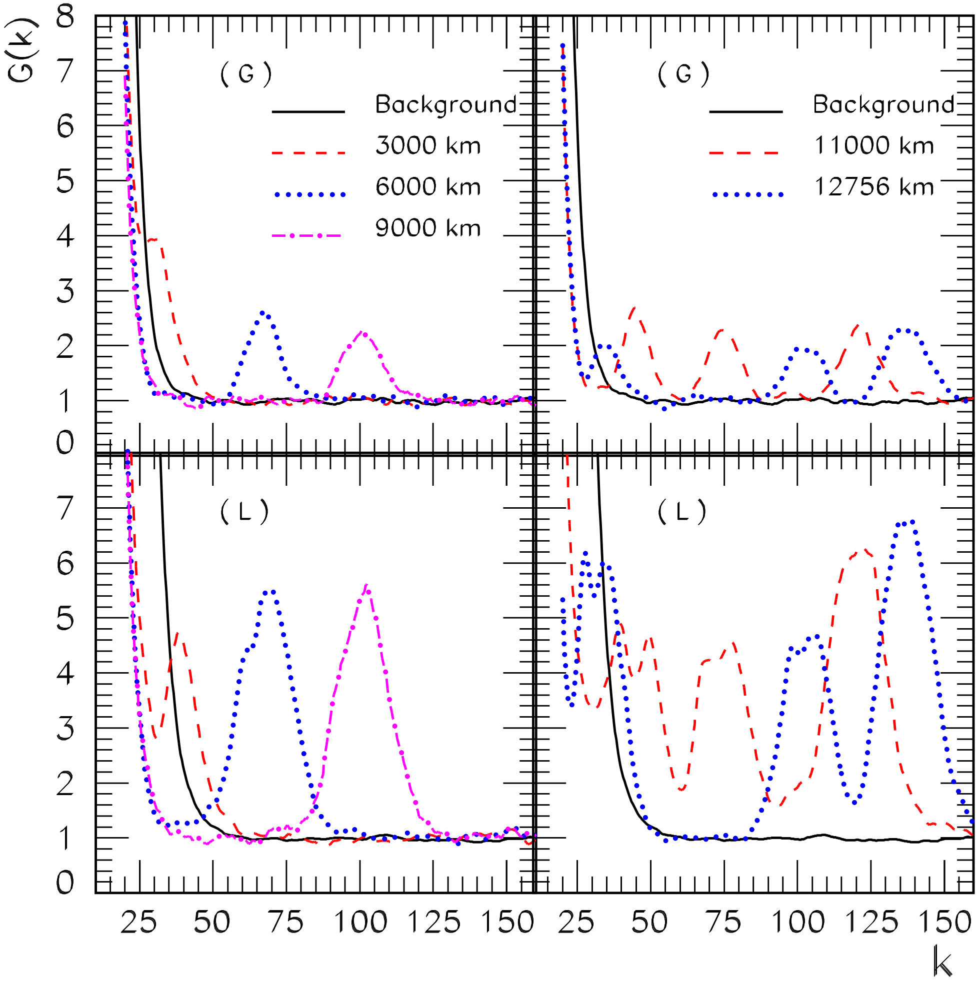
Oscillation frequency: $k_\oplus \equiv 2\overline{\Delta m^2_\oplus} L$

- 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
- 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)

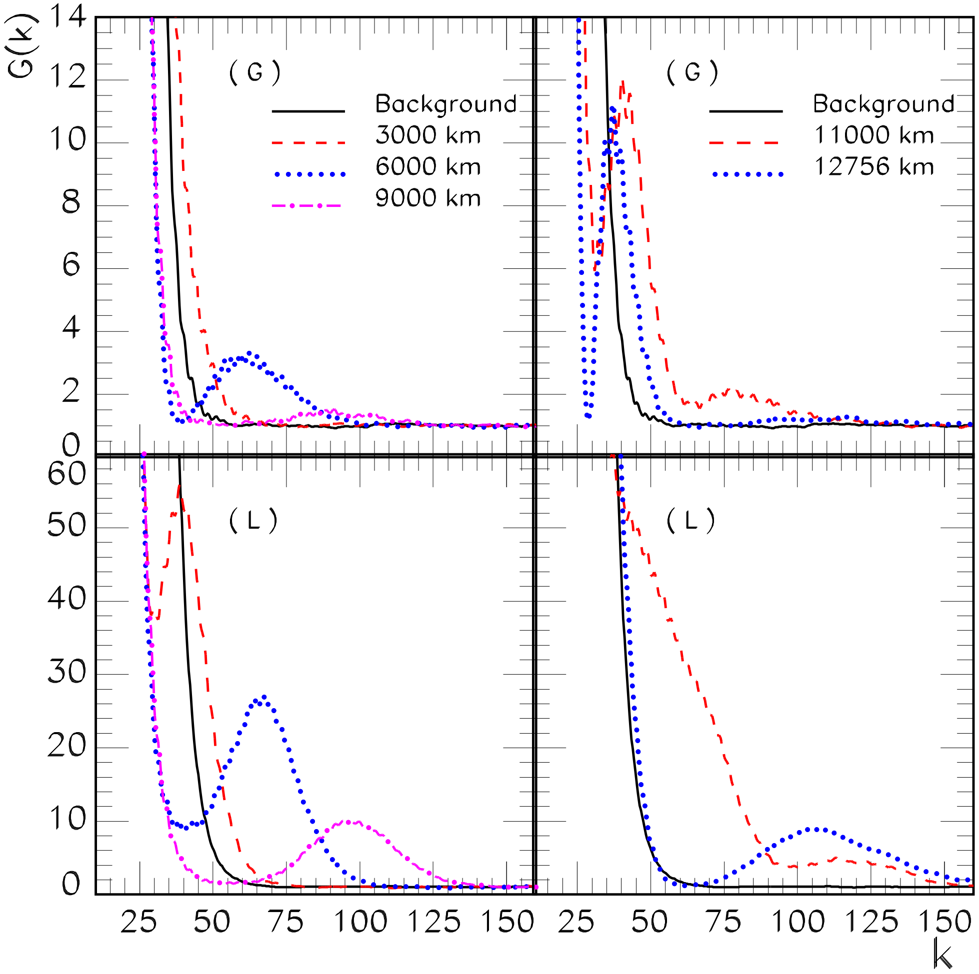
At a scintillation detector

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

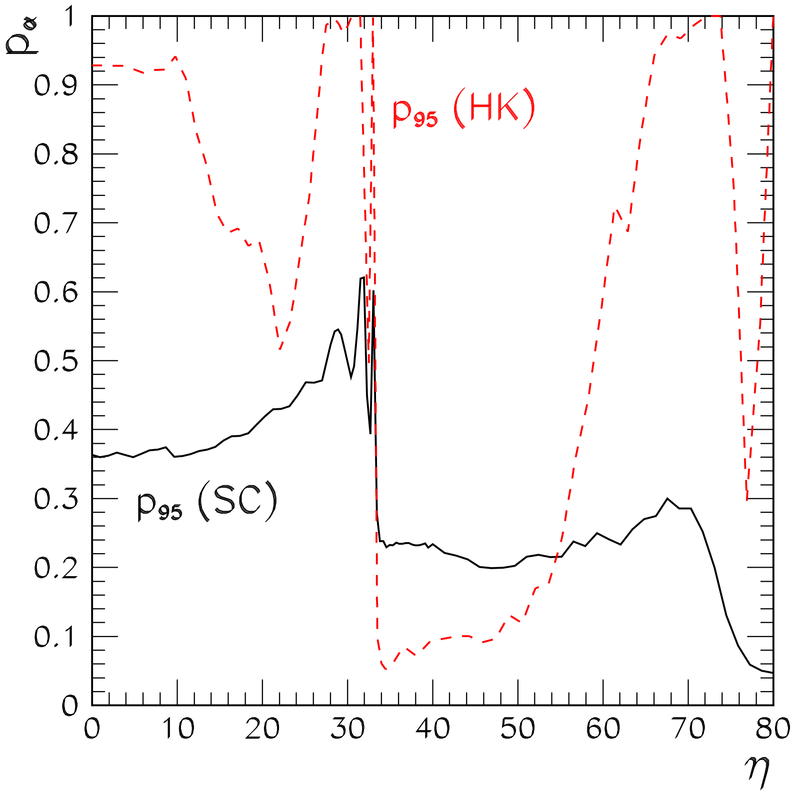


At a water Cherenkov detector

- 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 !!!

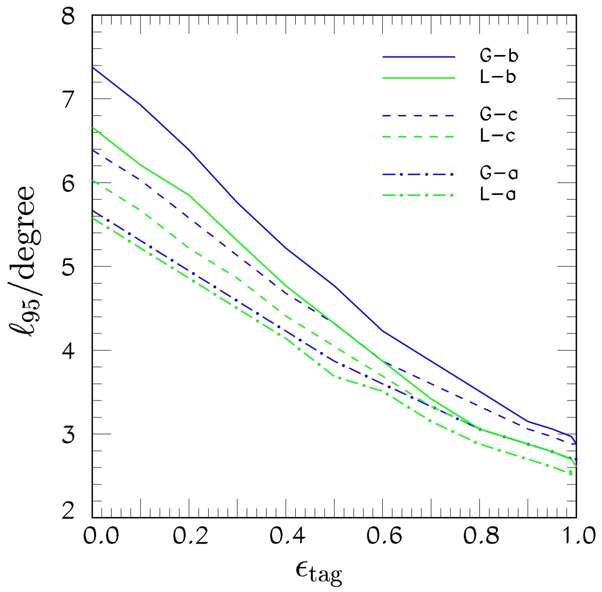
Neutrinos for SN astrophysics

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

Pointing to the SN in advance

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



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Pointing accuracy improved 2–3 times using Gd

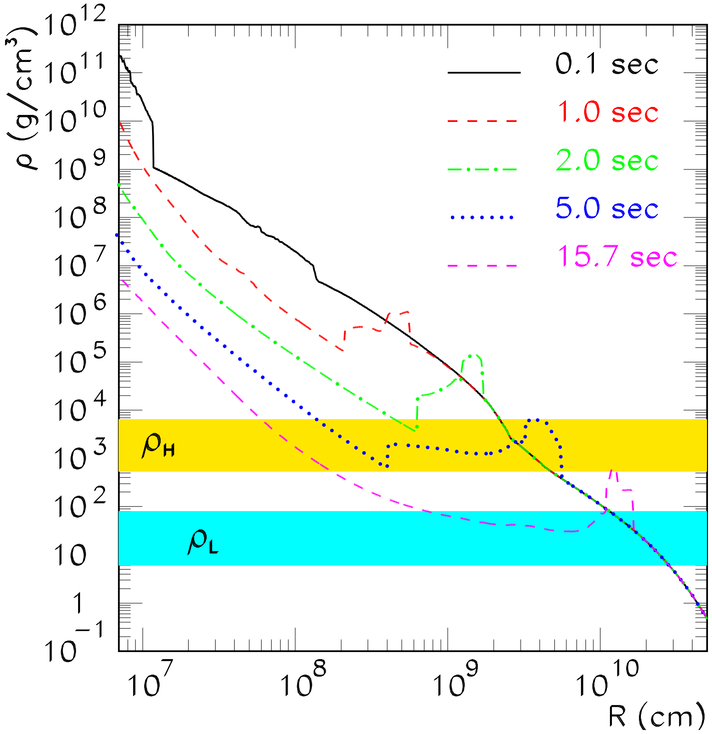
R. Tomàs, D. Semikoz, G. Raffelt,
M. Kachelrieß, AD
PRD 68, 093013 (2003).

GADZOOKS

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

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

Shock wave and level crossings

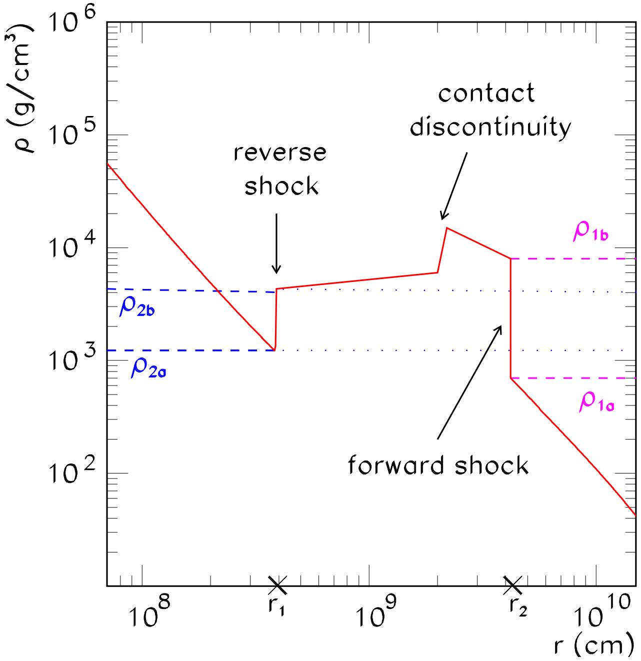


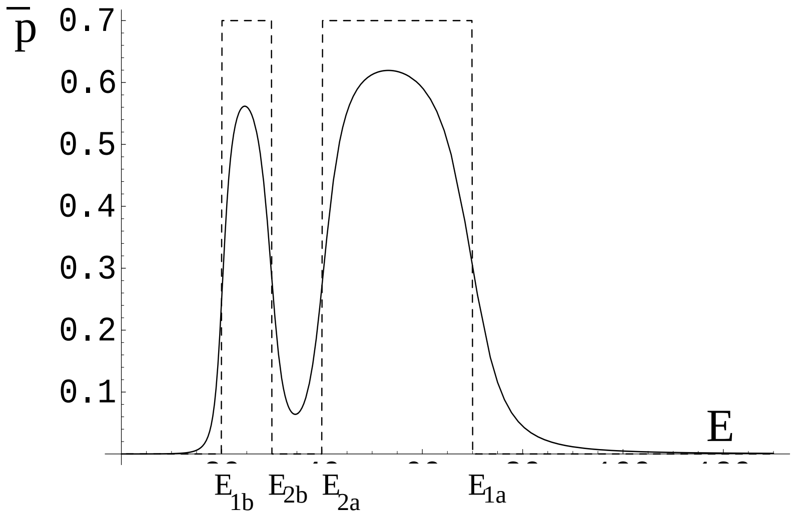
- When shock wave passes through a resonance region, adiabatic resonances may become non-adiabatic for some time
  scenario A → scenario C
  scenario B → scenario C
- May cause sharp changes in the final spectra even if the primary spectra are unchanged / smoothly changing

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

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

$\bar{\nu}_e$ Survival probability





$\longrightarrow$

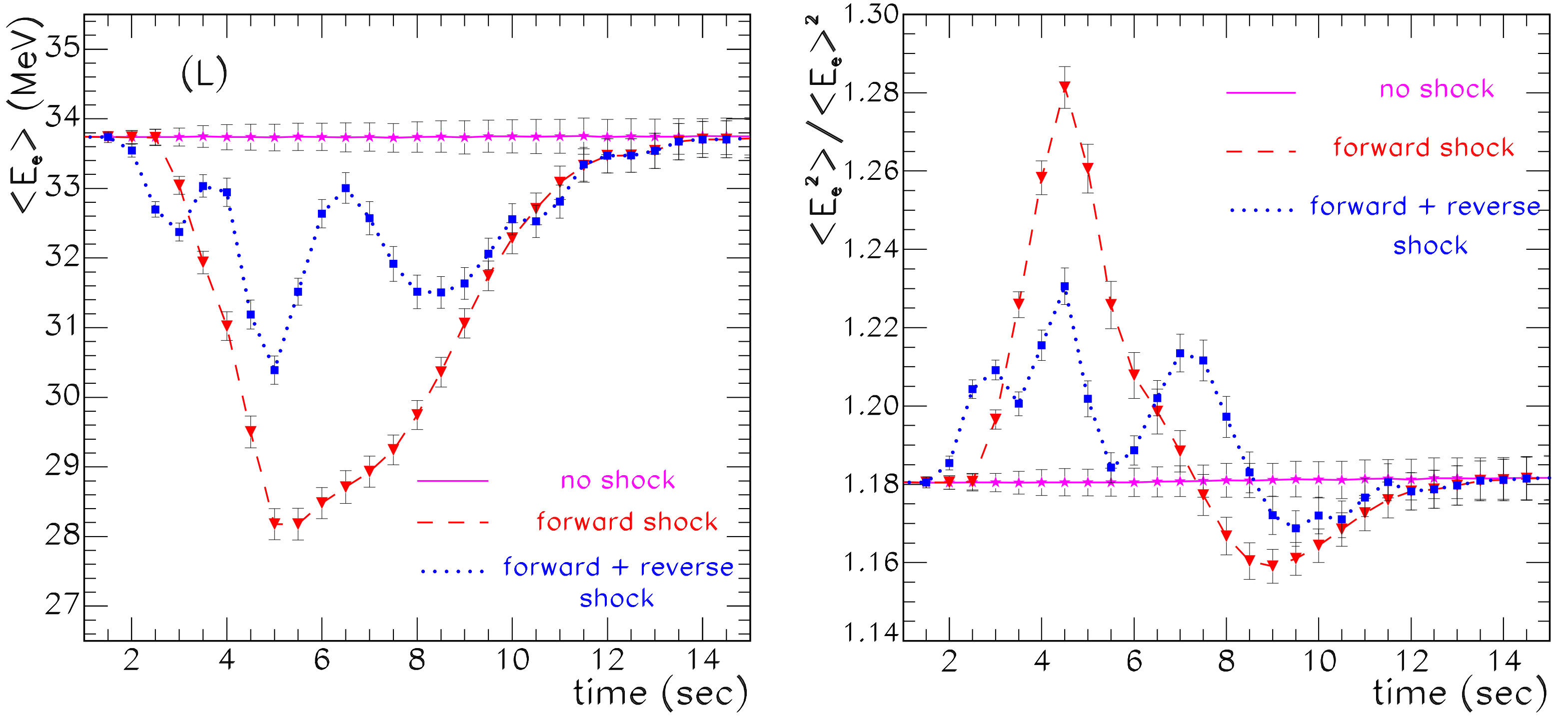
Shifts right as shock propagates to lower densities

Correspondence between densities and energies:

$$\rho_i = \frac{m_{\mathrm{N}}\Delta m^2_{\mathrm{atm}}\cos 2\theta_{13}}{2\sqrt{2}G_{\mathrm{F}}Y_{\mathrm{e}}E_i} \approx 600\,\mathrm{g/cm}^3\ \cos 2\theta_{13}\,\frac{25\ \mathrm{MeV}}{E_i}\,\frac{1}{Y_{\mathrm{e}}}$$

For sharp changes in the density profile: $\bar{p} = \sin^2(\theta_a - \theta_b)\cos^2\theta_\odot$

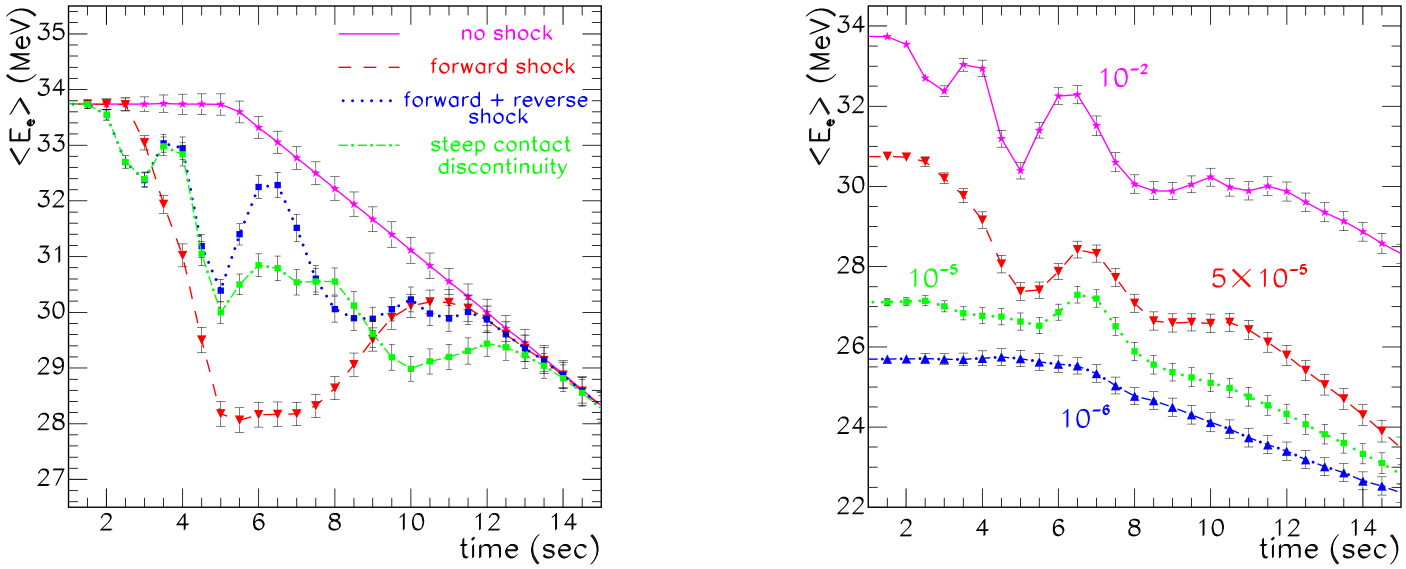
At a megaton water Cherenkov



- “Double dip” feature for $\langle E_e \rangle$
- “Double peak” feature for $\langle E_e^2 \rangle / \langle E_e \rangle^2$

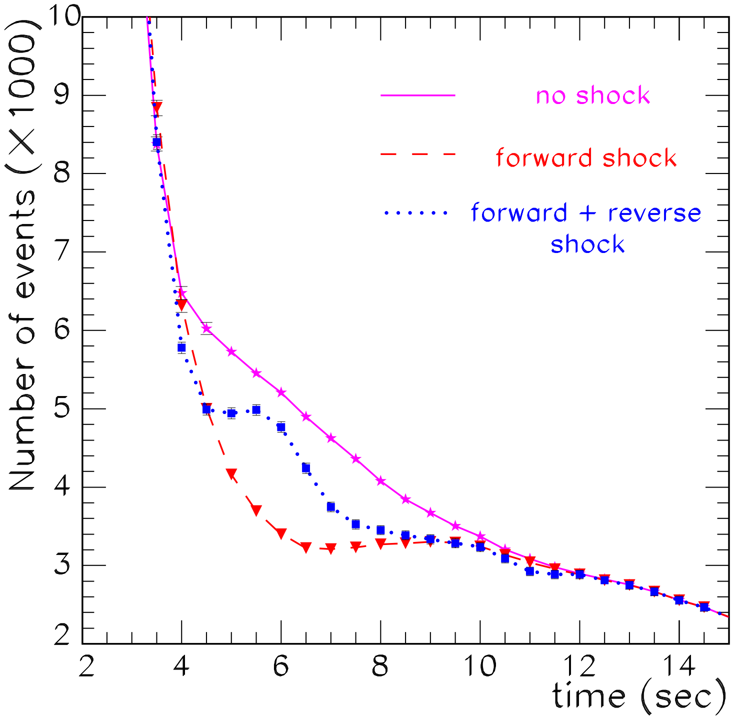
R. Tomás, M. Kachelrieß, G. Raffelt, AD,
H. T. Janka, L. Scheck, JCAP09(2004)015

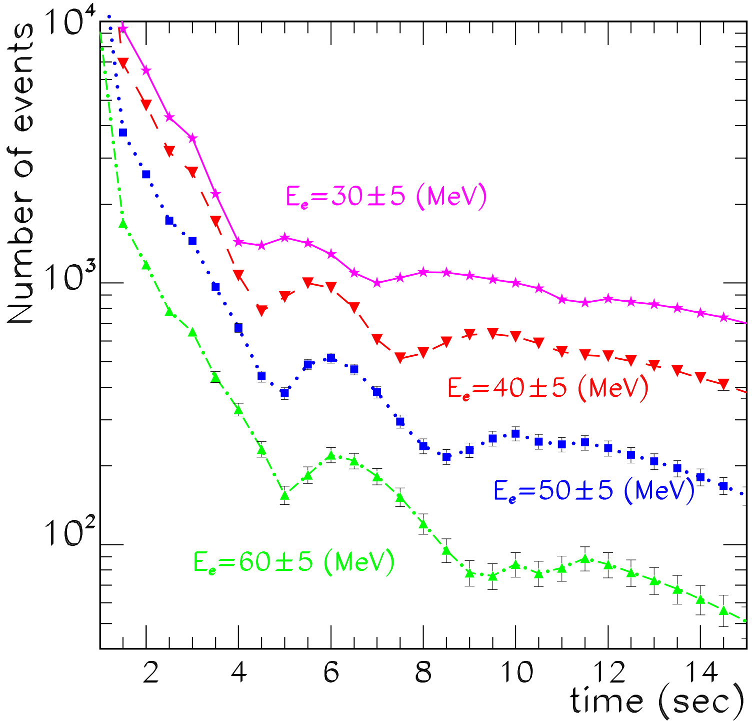
Single/double dip



- “Single/double dip” robust under
  - neutrino flux models
  - monotonically decreasing average energy
- “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

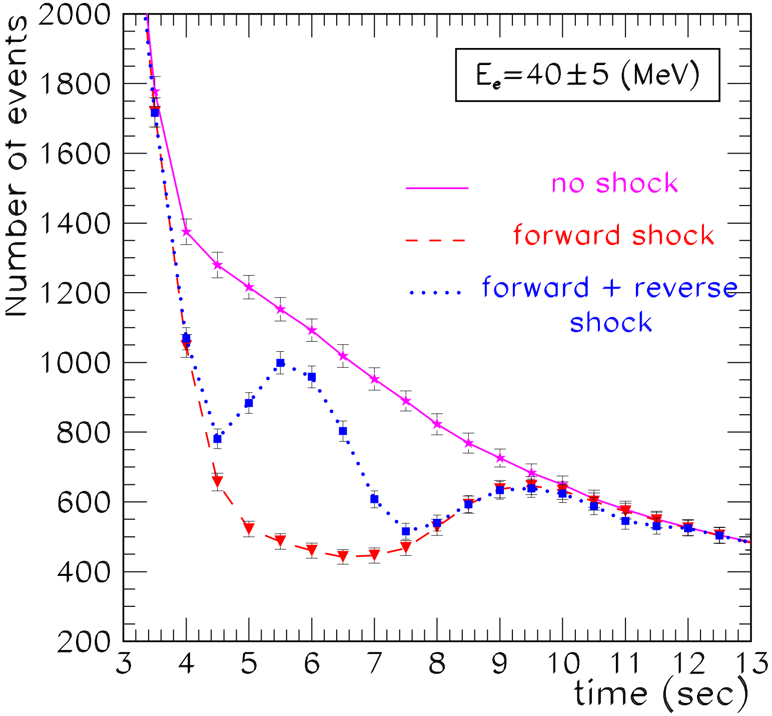
Splitting events into energy bins

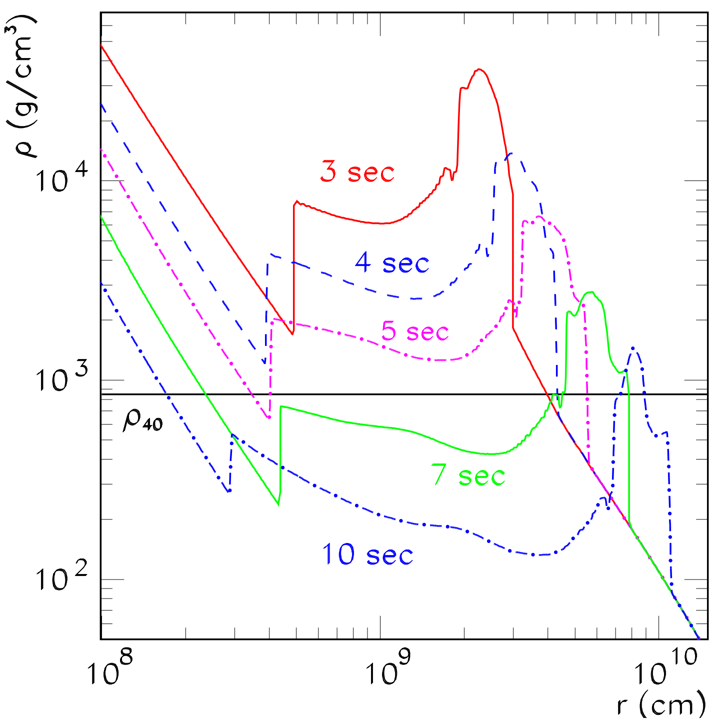




- Dip-times energy-bin dependent !!!

Tracking the shock fronts





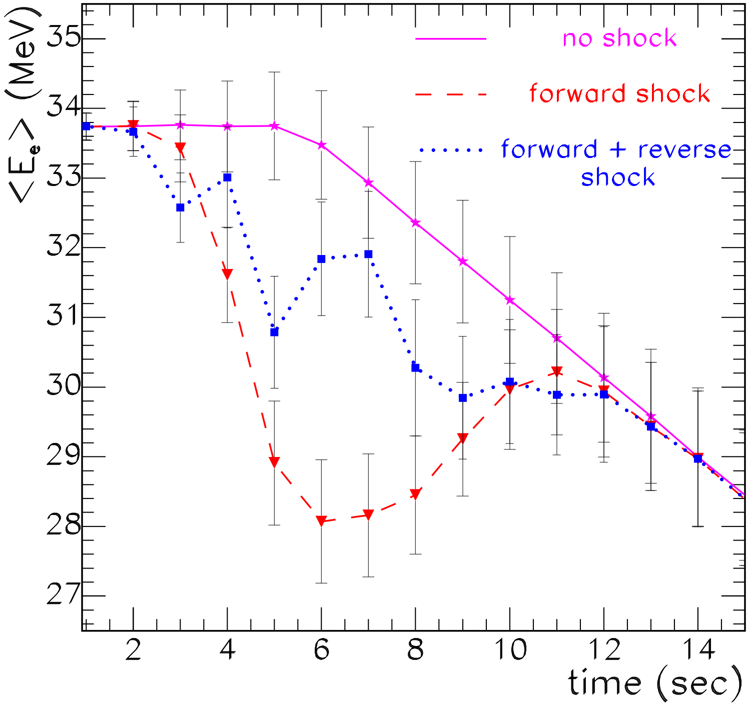
- At $t \approx 4.5$ sec, (reverse) shock at ρ_{40}
- At $t \approx 7.5$ sec, (forward) shock at ρ_{40}
- Multiple energy bins $\Rightarrow$ the times the shock fronts reach different densities of $\rho \sim 10^2$–10^4 g/cc

Summary [Detector wishlist]

- SN ν spectra can help identifying the neutrino mixing scenario:
  - normal / inverted mass hierarchy
  - small / large θ_{13}
- A positive identification of the Earth effects rules out scenario B (inverted hierarchy $\oplus \sin^2\Theta_{13} > 10^{-3}$) from $\bar{\nu}_e$ or scenario A (normal hierarchy $\oplus \sin^2\Theta_{13} > 10^{-3}$) through ν_e.
  - comparison between multiple detectors [SK/MWC, IceCube]
  - identifying earth matter oscillations [SK/MWC, LENA, liquid Ar]
- Advance SN pointing accuracy with neutrinos: less than 10°
  - can be improved 2–3 times using Gd [SK/MWC] to tag neutrons.
- Tracking the shock fronts “in neutrinos”
  - recognizes the presence / absence of a reverse shock
  - determines the times the shocks pass through $\rho \sim 10^2$–10^4 g/cc
  - confirms the scenario A [liquid Ar] or scenario B [MWC].

Extra slides

Shock wave at SK



Time evolution of observables

Primary spectra:

$$F_i^0(E) = \frac{\Phi_i}{\langle E_i \rangle} \frac{\beta_i^{\beta_i}}{\Gamma(\beta_i)} \left(\frac{E}{\langle E_i \rangle}\right)^{\beta_i - 1} \exp\left(-\beta_i \frac{E}{\langle E_i \rangle}\right)$$

Number of events:

$$N_{\rm obs} = \mathcal{N}\left[\Phi_{\bar\nu_x} \frac{\langle E_{\bar\nu_x} \rangle^2}{\beta_{\bar\nu_x}^2} \frac{\Gamma(\beta_{\bar\nu_x} + 2)}{\Gamma(\beta_{\bar\nu_x})} + \cos^2\theta_\odot (\Phi_{\bar\nu_e} g_2^{\bar\nu_e} - \Phi_{\bar\nu_x} g_2^{\bar\nu_x})\right]$$

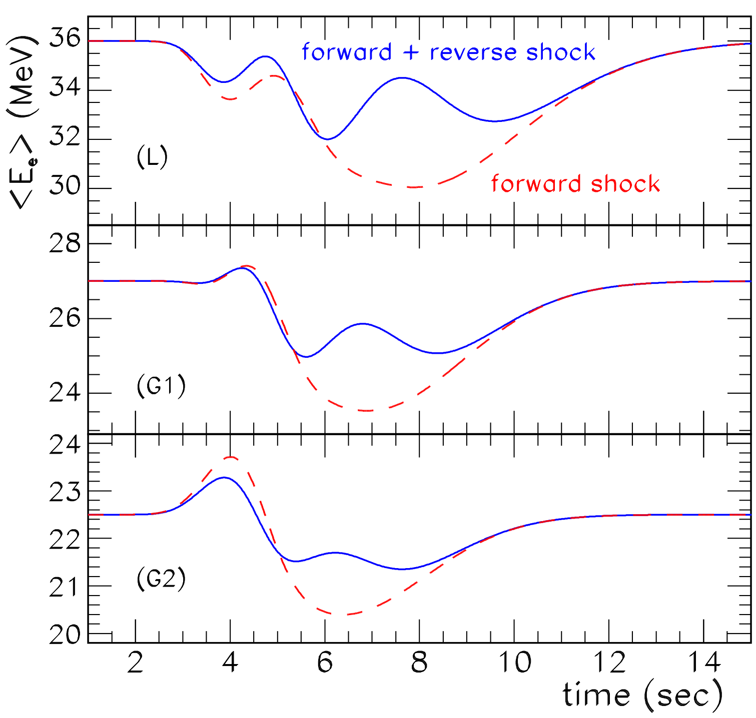
where $g_k^i = \frac{\langle E_{\bar\nu_x} \rangle^k}{\beta_i^k \Gamma(\beta_i)} \left[\Gamma\left(a, \frac{E_1}{\langle E_i \rangle}\beta_i, \frac{E_2}{\langle E_i \rangle}\beta_i\right) + \Gamma\left(a, \frac{E_3}{\langle E_i \rangle}\beta_i, \frac{E_4}{\langle E_i \rangle}\beta_i\right)\right]$

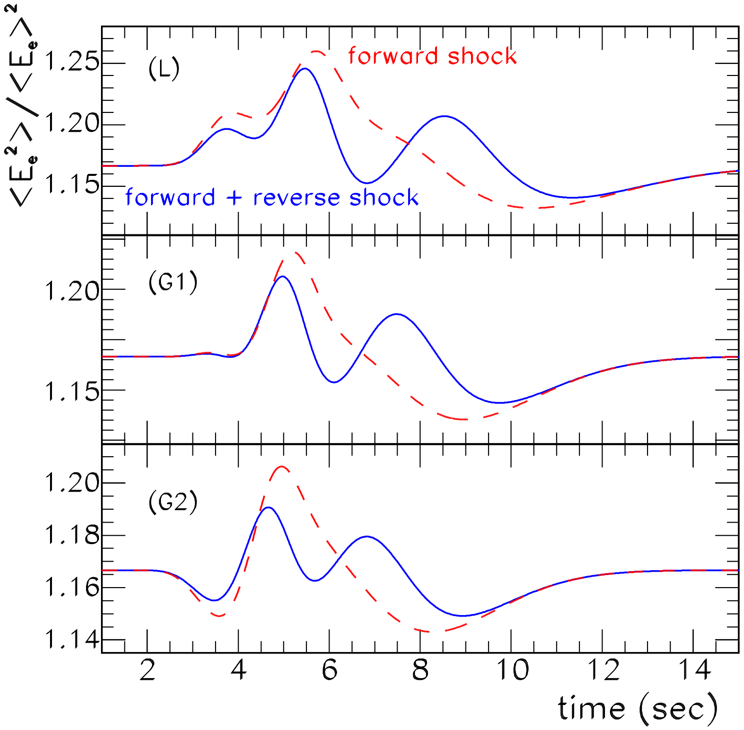
(Time dependence through the time evolution of E_1, E_2, E_3, E_4)

Energy moments:

$$E_{\rm obs}^m = \mathcal{N}\left[\Phi_{\bar\nu_x} \frac{\langle E_{\bar\nu_x} \rangle^{2+m}}{\beta_{\bar\nu_x}^{2+m}} \frac{\Gamma(\beta_{\bar\nu_x} + 2 + m)}{\Gamma(\beta_{\bar\nu_x})} + \cos^2\theta_\odot (\Phi_{\bar\nu_e} g_{2+m}^{\bar\nu_e} - \Phi_{\bar\nu_x} g_{2+m}^{\bar\nu_x})\right]$$

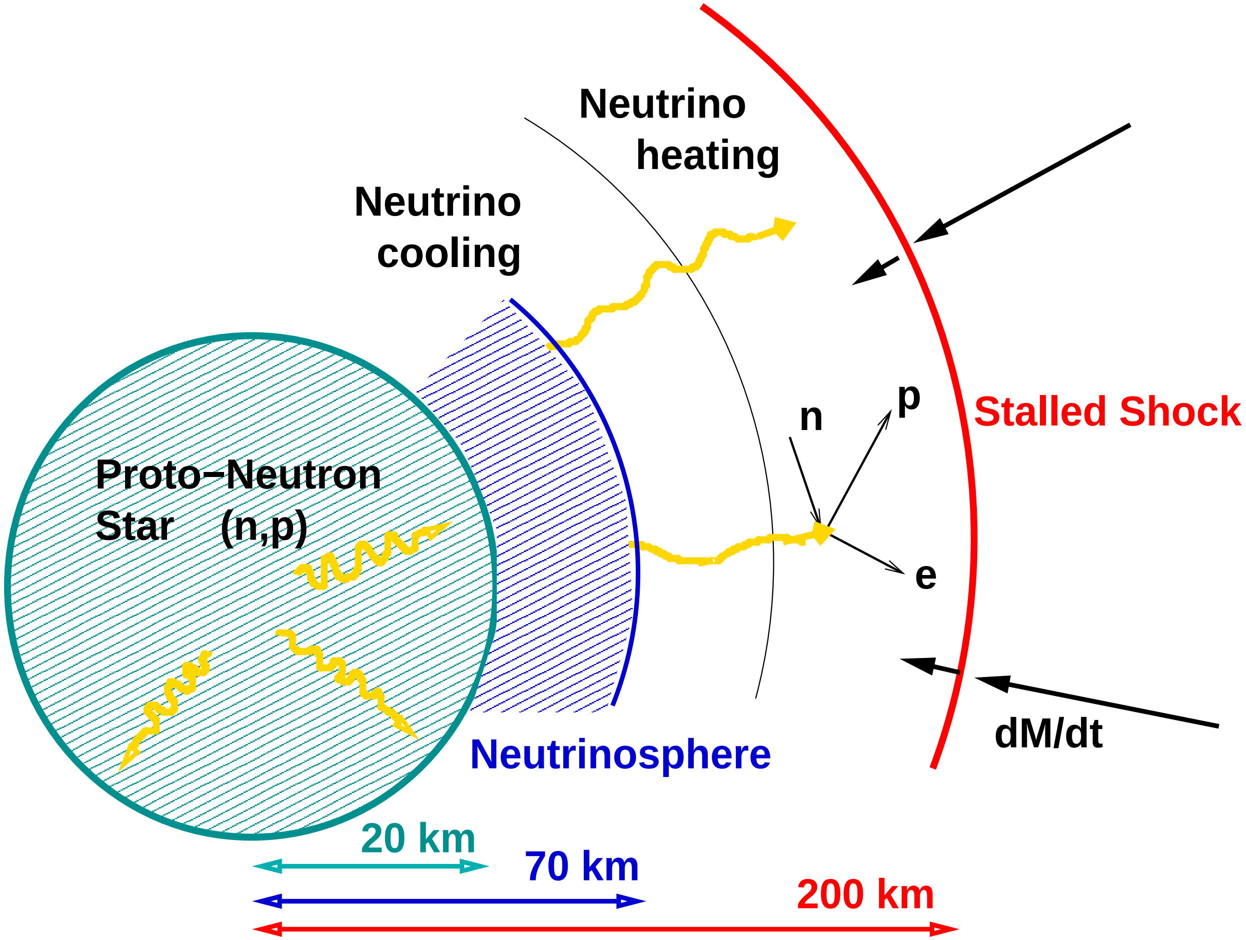
Time dependence of observables





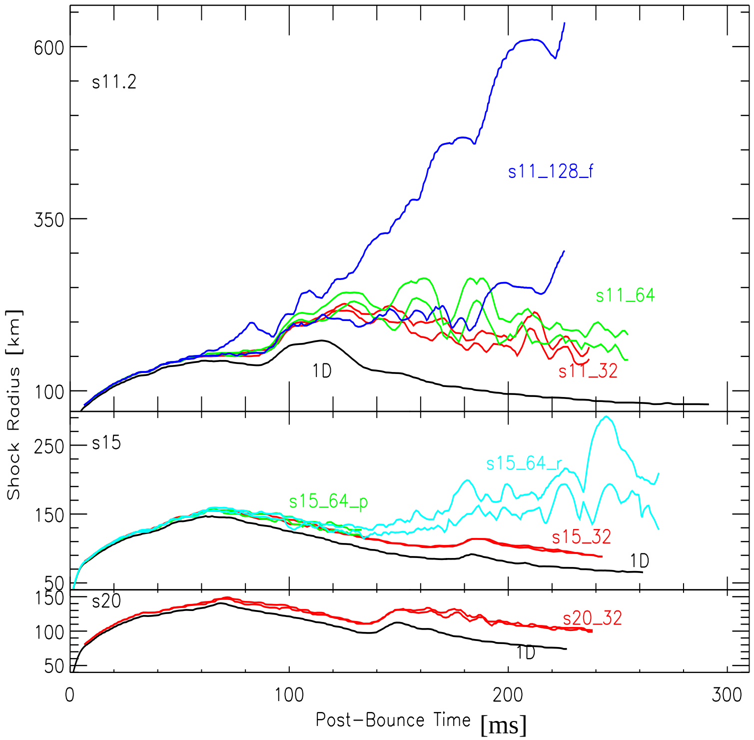
Model	$\langle E_0(\nu_e)\rangle$	$\langle E_0(\bar{\nu}_e)\rangle$	$\langle E_0(\nu_x)\rangle$	$\frac{\Phi_0(\nu_e)}{\Phi_0(\nu_x)}$	$\frac{\Phi_0(\bar{\nu}_e)}{\Phi_0(\nu_x)}$
L	12	15	24	2.0	1.6
G1	12	15	18	0.8	0.8
G2	12	15	15	0.5	0.5

Role of neutrinos in explosion



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

Ingredients 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

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A. Mezzacappa, W. Raphael Hix, F.-K. Thielemann *et al*