Physics Potential of Future Supernova Neutrino Observations

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Mumbai, India

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Supernova for neutrino physics and astrophysics

SN for neutrino oscillation phenomenology

- Detection of nonzero angle *you-know-who*
- Normal vs. inverted mass ordering
  (both possible even if $\theta_{13} \to 0$)

Neutrino detection for SN astrophysics

- Pointing to the SN in advance
- Tracking SN shock wave in neutrinos
- Diffuse SN neutrino background

The flavour of this talk

- Only standard three-neutrino mixing
- Only standard SN explosion scenario
- Concentrate on the exciting developments in the last two years: *"neutrino refraction / collective effects"*

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2. Neutrino propagation and flavor conversions
   - Matter effects inside the star: collective and MSW
   - Earth matter effects
   - Shock wave effects
3. Smoking gun signals
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   - During the accretion and cooling phase
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Neutrino emission

Gravitational core collapse $\Rightarrow$ Shock Wave

Neutronization burst:

ν_e emitted for $\sim$ 10 ms

Cooling through neutrino emission: $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$

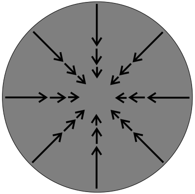
Duration: About 10 sec

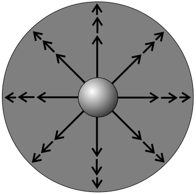
Emission of 99% of the SN energy in neutrinos

¿¿¿ *Explosion* ???

Neutrino emission

Gravitational core collapse $\Rightarrow$ Shock Wave





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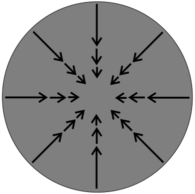

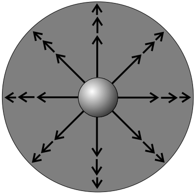

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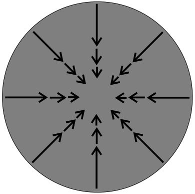

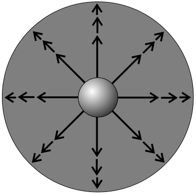

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Primary fluxes and spectra

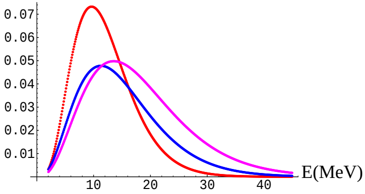
Neutrino fluxes:

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

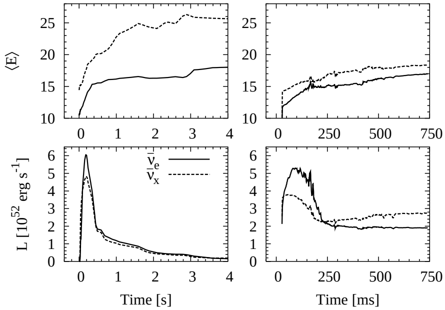
E_0, α: in general time dependent

- Energy hierarchy: $E_0(\nu_e) < E_0(\bar{\nu}_e) < E_0(\nu_x)$

$E_0(\nu_e) \approx 10$–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



Flavor-dependence of neutrino fluxes



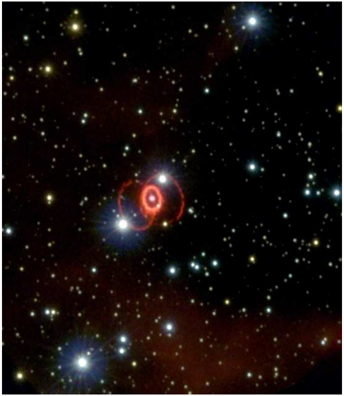
solid line: $\bar{\nu}_e$
dotted line: $\bar{\nu}_x$

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)

Outline

SN1987A



(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

Signal expected from a galactic SN (10 kpc)

Water Cherenkov detector:

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

* Events expected at Super-Kamiokande with a galactic SN at 10 kpc

Carbon-based scintillation detector:

- $\bar{\nu}_e p \rightarrow n e^+$
- $\nu + {}^{12}C \rightarrow \nu + X + \gamma$ (15.11 MeV)

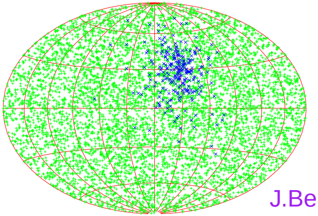
Liquid Argon detector:

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

Pointing to the SN in advance

- Neutrinos reach 6-24 hours before the light from SN explosion (SNEWS network)
- $\bar{\nu}_e p \to n e^+$: nearly isotropic background
- $\nu e^- \to \nu e^-$: forward-peaked "signal"
- Background-to-signal ratio: $N_B/N_S \approx 30$–50
- SN at 10 kpc may be detected within a cone of $\sim 5^\circ$ at SK

J. Beacom and P. Vogel, PRD 60, 033007 (1999)



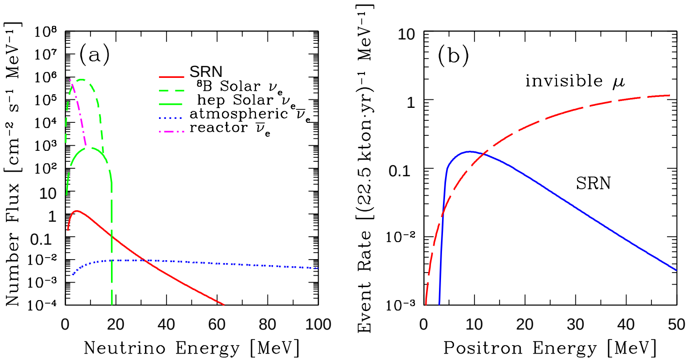
Neutron tagging with Gd improves the pointing accuracy 2–3 times

R.Tomàs *et al.*, PRD 68, 093013 (2003).

GADZOOKS

J.Beacom and M.Vagins, PRL 93, 171101 (2004)

Diffuse SN neutrino background



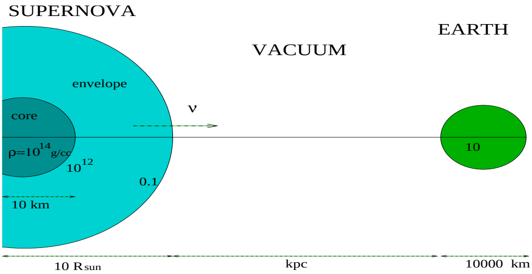
- Within reach of HK, easier if Gd added
- “Invisible muon” background needs to be taken care of

S. Ando and K. Sato, New J. Phys. 6, 170 (2004)

S.Chakraborti, B.Dasgupta, S.Choubey, K.Kar, arXiv:0805.xxxx

Outline

Propagation through matter of varying density



Inside the SN: *flavour conversion*

Collective effects and MSW matter effects

Between the SN and Earth: *no flavour conversion*

Mass eigenstates travel independently

Inside the Earth: *flavour conversion*

MSW matter effects (*if detector is on the other side*)

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Nonlinear effects due to $\nu - \nu$ coherent interactions

- Large neutrino density $\Rightarrow$ substantial ν–ν potential

$$H = H_{vac} + H_{MSW} + H_{\nu\nu}$$

$$\begin{aligned} H_{vac}(\vec{p}) &= M^2/(2p) \\ H_{MSW} &= \sqrt{2} G_F n_{e^-} diag(1,0,0) \\ H_{\nu\nu}(\vec{p}) &= \sqrt{2} G_F \int \frac{d^3q}{(2\pi)^3} (1 - \cos\theta_{pq}) (\rho(\vec{q}) - \bar{\rho}(\vec{q})) \end{aligned}$$

- Coherent scattering and nonlinear effects

General formalism:

J. Pantaleone, M.Thomson, B.McKellar, V.A.Kostelecky, S. Samuel, G.Sigl, G.G.Raffelt, *et al.*, (1992-1998)

Numerical simulations in SN context:

H. Duan, G. Fuller, J. Carlson, Y. Qian, *et al.* (2006-2008)

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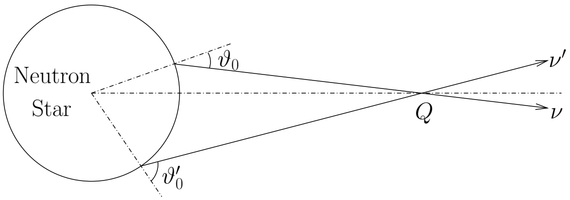
Multi-angle effects



H. Duan, G. Fuller, J. Carlson, Y. Qian,PRL 97, 241101 (2006)

- “Multi-angle decoherence” during collective oscillations suppressed by ν–$\bar{\nu}$ asymmetry

A.Esteban-Pretel, S.Pastor, R.Tomas, G.Raffelt, G.Sigl, PRD76, 125018 (2007)

Poster by A. Esteban-Pretel

- “Single-angle” evolution along lines of neutrino flux works even for non-spherical geometries, as long as coherence is maintained

B.Dasgupta, AD, A.Mirizzi, G.Raffelt, arXiv:0805.xxxx

“Collective” effects: analytical understanding

Synchronized oscillations:

ν and $\bar{\nu}$ of all energies oscillate with the same frequency

S. Pastor, G. Raffelt and D. Semikoz, PRD65, 053011 (2002)

Bipolar oscillations:

Coherent $\nu_e \bar{\nu}_e \leftrightarrow \nu_x \bar{\nu}_x$ pairwise conversions even for extremely small θ_{13} (in IH)

S. Hannestad, G. Raffelt, G. Sigl, Y. Wong, PRD74, 105010 (2006)

Spectral split:

In inverted hierarchy, $\bar{\nu}_e$ and $\bar{\nu}_x$ spectra interchange completely.
ν_e and ν_x spectra interchange only above a certain critical energy.

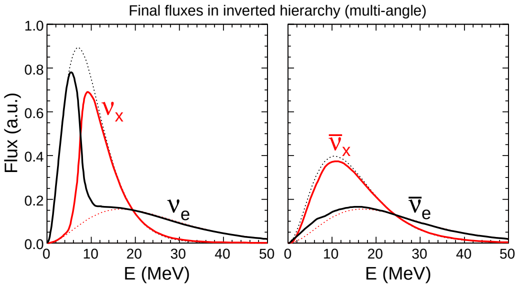
G.Raffelt, A.Smirnov, PRD76, 081301 (2007), PRD76, 125008 (2007)

Collective effects: some insights

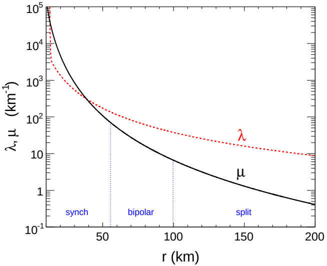
- Synchronized oscillations ⇒ No significant flavour changes
- Bipolar oscillations ⇒ preparation for spectral split

- Multi-angle effects only smear the spectra to some extent

G.L.Fogli, E. Lisi, A. Marrone, A. Mirizzi, JCAP 0712, 010 (2007)



Collective effects vs. MSW effects (two-flavor)

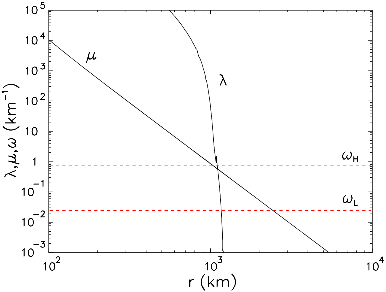


- $\mu \equiv \sqrt{2} G_F (N_\nu + N_{\bar{\nu}})$
- $\lambda \equiv \sqrt{2} G_F N_e$

- $r \lesssim 200$ km: collective effects dominate
- $r \gtrsim 200$ km: standard MSW matter effects dominate

G.L.Fogli, E. Lisi, A. Marrone, A. Mirizzi, JCAP 0712, 010 (2007)

O-Ne-Mg supernovae



H. Duan, G. M. Fuller, J. Carlson Y.Z.Qian, PRL100, 021101 (2008)

C. Lunardini, B. Mueller and H. T. Janka, arXiv:0712.3000

- MSW resonances occur while collective effects are still dominant
- All neutrinos resonate together, the same adiabaticity for all
- Interesting spectral split features

Three-flavor collective effects

Three-flavor results by combining two-flavor ones

- Factorization in two two-flavor evolutions possible
- Pictorial understanding through “flavour triangle” diagrams

B.Dasgupta and AD, arXiv:0712.3798, PRD

Poster by B. Dasgupta

New three-flavor effects

- In early accretion phase, large μ-τ matter potential causes interference between MSW and collective effects, *sensitive to deviation of* θ_{23} *from maximality*

A.Esteban-Pretel, S.Pastor, R.Tomas, G.Raffelt, G.Sigl, PRD77, 065024 (2008)

Poster by S. Pastor

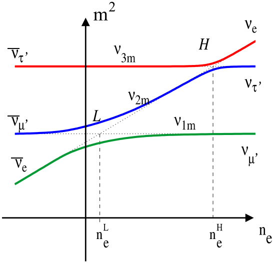
- Spectral splits develop at two energies, in a stepwise process

H.Duan, G.M.Fuller and Y.Z.Qian, arXiv:0801.1363

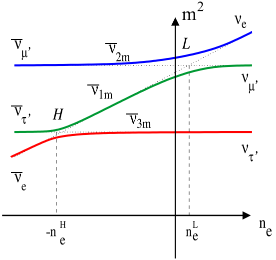
B.Dasgupta, AD, A.Mirizzi and G. G. Raffelt, arXiv:0801.1660

MSW Resonances inside a SN

Normal mass ordering



Inverted mass ordering



AD, A.Smirnov, PRD62, 033007 (2000)

H resonance: $(\Delta m^2_{\rm atm}, \theta_{13})$, $\rho \sim 10^3$–10^4 g/cc

- In $\nu(\bar{\nu})$ for normal (inverted) hierarchy
- Adiabatic (non-adiabatic) for $\sin^2\theta_{13} \gtrsim 10^{-3} (\lesssim 10^{-5})$

L resonance: $(\Delta m^2_\odot, \theta_\odot)$, $\rho \sim 10$–100 g/cc

- Always adiabatic, always in ν

Fluxes arriving at the Earth

Mixture of initial fluxes:

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

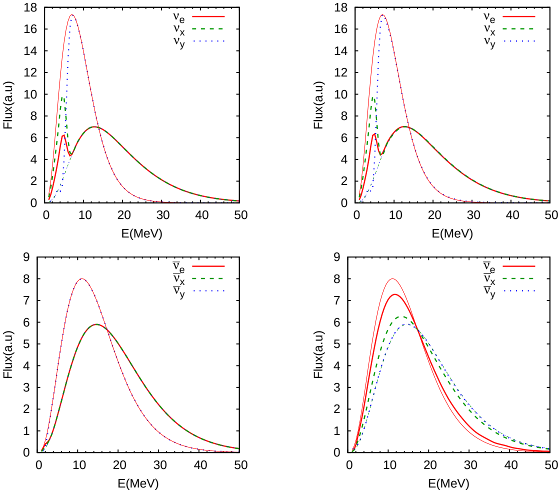
Survival probabilities in different scenarios:

	Hierarchy	$\sin^2\theta_{13}$	p	$\bar{p}$
A	Normal	Large	0	$\sin^2\theta_\odot$
B	Inverted	Large	$\cos^2\theta_\odot \mid 0$	$\cos^2\theta_\odot$
C	Normal	Small	$\sin^2\theta_\odot$	$\cos^2\theta_\odot$
D	Inverted	Small	$\cos^2\theta_\odot \mid 0$	0

- "Small": $\sin^2\theta_{13} \lesssim 10^{-5}$, "Large": $\sin^2\theta_{13} \gtrsim 10^{-3}$.
- All four scenarios separable in principle !!

B. Dasgupta, AD, arXiv:0712.3798, PRD

Final spectra for inverted hierarchy



Neutrinos

Antineutrinos

Small θ_{13}

Large θ_{13}

B.Dasgupta, AD, arXiv:0712.3798, PRD

Normal vs. inverted hierarchy even when $\theta_{13} \to 0$??

Survival probabilities in different scenarios:

	Hierarchy	$\sin^2\theta_{13}$	p	$\bar{p}$
A	Normal	Large	0	$\sin^2\theta_\odot$
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C	Normal	Small	$\sin^2\theta_\odot$	$\cos^2\theta_\odot$
D	Inverted	Small	$\cos^2\theta_\odot \mid 0$	0

- Spectral split in neutrinos present for IH, absent for NH

  H.Duan, G.M.Fuller, J.Carlson and Y.Q.Zhong, PRL 99, 241802 (2007)

- Earth matter effects in antineutrinos present in IH, absent for NH.

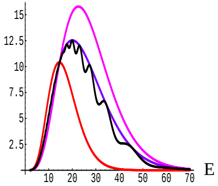
  B.Dasgupta, AD, A.Mirizzi, arXiv:0802.1481

- Valid even for $\sin^2\theta_{13} \lesssim 10^{-10}$!!

Outline

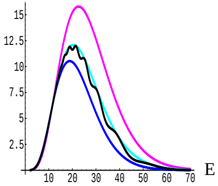
Earth matter effects

Neutrinos



(ν_e, ν_x, mixed ν)

Antineutrinos



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

- Total number of events change
- “Earth effect” oscillations are introduced

Presence or absence of Earth matter effects:

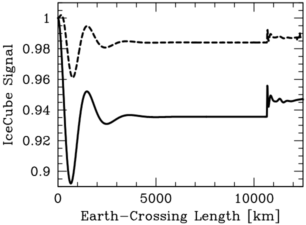
	Hierarchy	$\sin^2\theta_{13}$	ν_e	$\bar{\nu}_e$
A	Normal	Large	X	√
B	Inverted	Large	X	√
C	Normal	Small	√	√
D	Inverted	Small	X	X

IceCube as a co-detector with HK

- Total Cherenkov count in IceCube increases beyond statistical backround fluctuations during a SN burst

  F.Halzen, J.Jacobsen, E.Zas, PRD53, 7359 (1996)

- This signal can be determined to a statistical accuracy of $\sim$ 0.25% for a SN at 10 kpc.
- 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)

Collective effects will change the ratio

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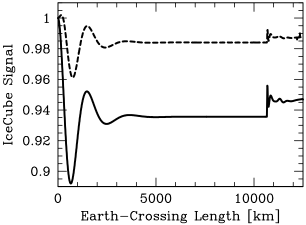


AD, M. Keil, G. Raffelt,
JCAP 0306:005 (2003)

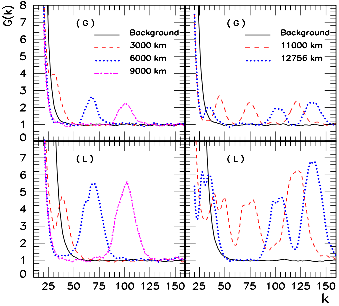
Collective effects will change the ratio

Earth effects through Fourier Transform

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

$(y \equiv 25\ MeV/E)$

- Model independence of peak positions at a scintillator:



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

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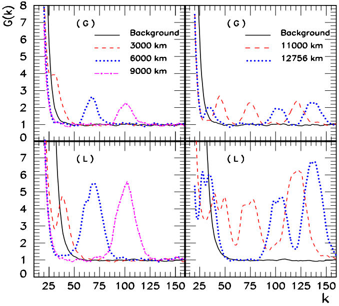
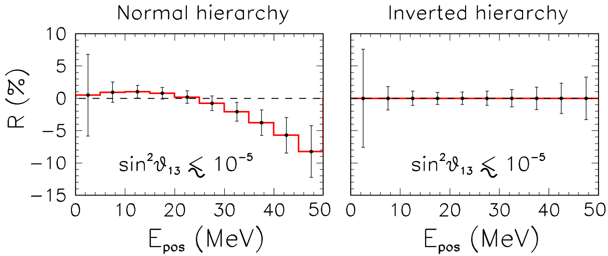


AD, M. Kachelrieß, G. Raffelt, R. Tomàs, JCAP 0401:004 (2004)

Collective effects will not change peak positions

Earth matter effects from two Water Cherenkovs

$$R \equiv \frac{N(shadowed) - N(unshadowed)}{N(unshadowed)}$$



Robust experimental signature, thanks to Collective Effects

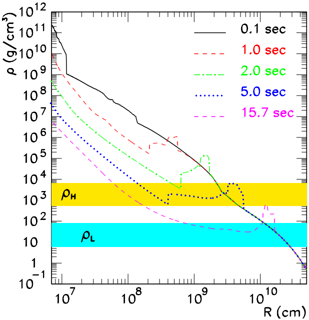
- Earth effects can distinguish hierarchies even for $\theta_{13} \to 0$

B.Dasgupta, AD, A. Mirizzi, arXiv:0802.1481

Outline

Shock wave and adiabaticity breaking

When shock wave passes through a resonance region (density ρ_H or ρ_L):

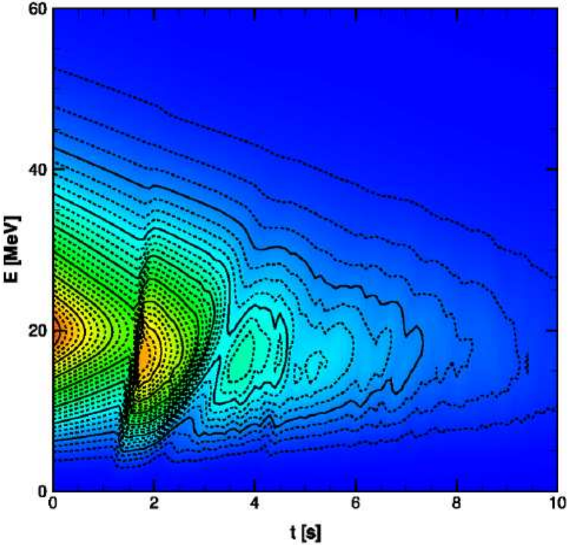


- adiabatic resonances may become momentarily non-adiabatic
  scenario A $\longrightarrow$ scenario C
  scenario B $\longrightarrow$ scenario D
- Sharp changes in the final spectra even if the primary spectra change smoothly

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

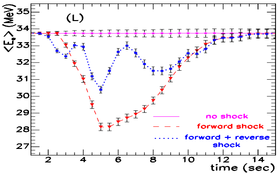
G. L. Fogli, E. Lisi, D. Montanino and A. Mirizzi, PRD 68, 033005 (2003)

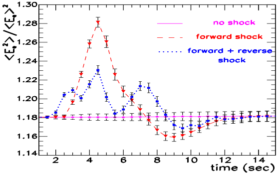
Time dependent spectral evolution



J.P.Kneller, G.C.Mclaughlin, J.Brockman, PRD77, 045023 (2008)

Double/single dip at a megaton water Cherenkov





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

Double/single dip

- robust under monotonically decreasing average energy
- In ν_e ($\bar{\nu}_e$) for normal (inverted) hierarchy for $\sin^2\theta_{13} \gtrsim 10^{-5}$

R.Tomas, M.Kachelriess, G.Raffelt, AD, H.T.Janka and L.Scheck
JCAP **0409**, 015 (2004)

Collective effects $\Rightarrow$ dip $\leftrightarrow$ peak

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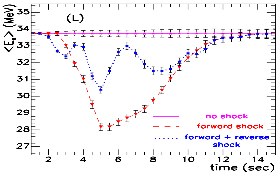

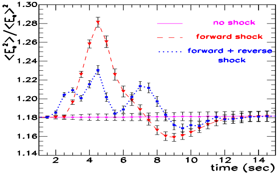

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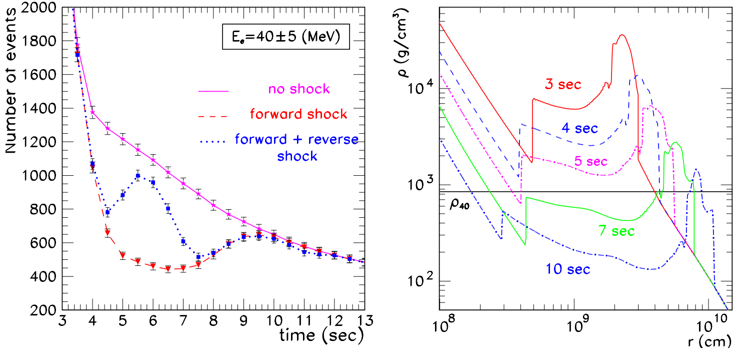
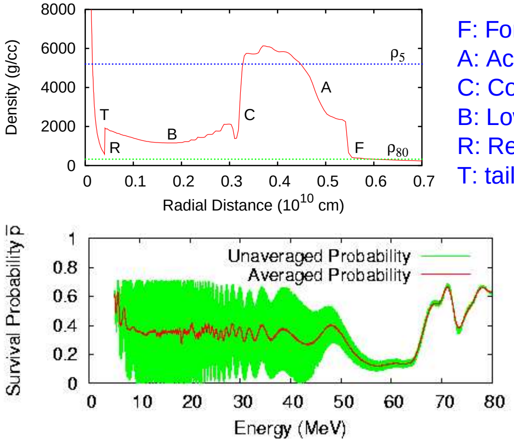
Tracking the shock fronts



- 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 ⇒ the times the shock fronts reach different densities of $\rho \sim 10^2$–10^4 g/cc

Shock wave giving rise to neutrino oscillations



F: Forward shock
A: Accretion region
C: Contact discontinuity
B: Low density "bubble"
R: Reverse shock
T: tail of the shock

- Oscillations smeared out at a water Cherenkov
- At a scintillator, $\mathcal{O}(10^5)$ events needed in a time bin

B. Dasgupta, AD, PRD 75, 093002 (2007)

Shock wave signals

Presence or absence of shock wave signal:

	Hierarchy	$\sin^2\theta_{13}$	ν_e	$\bar{\nu}_e$
A	Normal	Large	$\surd$	$\surd$
B	Inverted	Large	X	$\surd$
C	Normal	Small	X	X
D	Inverted	Small	X	X

Shock wave signal may be diluted by:

- Stochastic density fluctuations: may partly erase the shock wave imprint

  G. Fogli, E. Lisi, A. Mirizzi and D. Montanino, JCAP 0606, 012 (2006)

- Turbulent convections behind the shock wave: gradual depolarization effects

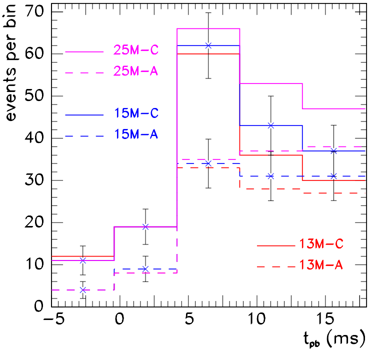
  A. Friedland and A. Gruzinov, astro-ph/0607244

  S.Choubey, N.Harries, G.G.Ross, PRD76, 073013 (2007)

Outline

Outline

Vanishing ν_e burst

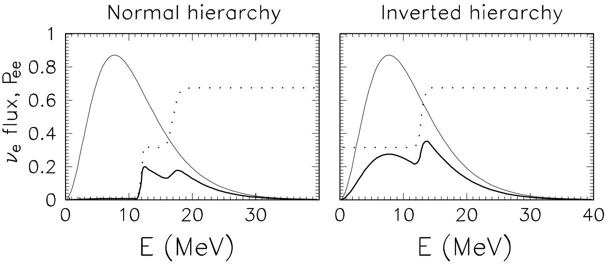


M. Kachelriess, R. Tomas, R. Buras, H. T. Janka, A. Marek and M. Rampp PRD **71**, 063003 (2005)

- Time resolution of the detector crucial for separating ν_e burst from the accretion phase signal

Burst signal vanishes for Normal hierarchy $\oplus$ large θ_{13}

Stepwise spectral split in O-Ne-Mg supernovae



- MSW resonances deep inside collective regions
- "MSW-prepared" spectral splits: two for NH, one for IH

H.Duan, G.Fuller, Y.Z.Qian, PRD77, 085016 (2008)

- Positions of splits fixed by initial spectra

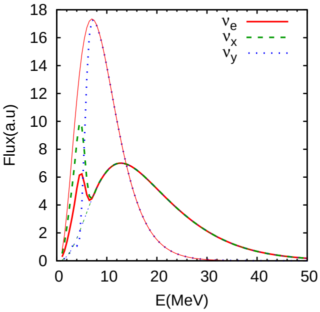
B.Dasgupta, AD, A. Mirizzi, G.G.Raffelt, arXiv:0801.1660, PRD

Stepwise ν_e suppression much more at low energy

- Identification of O-Ne-Mg supernova ??

Outline

Spectral split in ν_e



- Happens only in inverted hierarchy
- Takes place at low energies (5-10 MeV)
- Needs liquid Ar detector with a low threshold
- Signal at a detector almost washed out due to the difference in E_{ν_e} and E_{e^-} and detector resolution

Shock wave effects

Presence or absence of shock wave signal:

	Hierarchy	$\sin^2\theta_{13}$	ν_e	$\bar{\nu}_e$
A	Normal	Large	$\surd$	$\surd$
B	Inverted	Large	X	$\surd$
C	Normal	Small	X	X
D	Inverted	Small	X	X

- Time dependent spectral evolution

Dips / peaks in $\langle E^n \rangle$

Earth matter effects

Presence or absence of Earth matter effects:

	Hierarchy	$\sin^2\theta_{13}$	ν_e	$\bar{\nu}_e$
A	Normal	Large	X	$\surd$
• B	Inverted	Large	X	$\surd$
C	Normal	Small	$\surd$	$\surd$
D	Inverted	Small	X	X

- Comparison of IceCube/HK luminosities during accretion and cooling phases
- Earth effect oscillations through Fourier transforms of neutrino spectra
- Energy dependent ratio of events at shadowed/ unshadowed detectors

Outline

Concluding remarks

- Supernova neutrinos probe neutrino mass hierarchy and θ_{13} range, even for $\theta_{13} \to 0$, thanks to collective effects and MSW resonances inside the star
- Smoking gun signals of neutrino mixing scenarios through
  - Neutronization burst suppression
  - Time variation of signal during shock wave propagation
  - Earth matter effects
- Implications for SN astrophysics
  - Pointing to the SN in advance
  - Diffuse supernova neutrino background
  - Tracking the shock wave while still inside mantle

> A rare event is a lifetime opportunity
>
> – Anon

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