Supernova neutrino oscillations

What do we understand ?

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Supernova for neutrino physics and astrophysics

SN for neutrino oscillation phenomenology

- Normal vs. inverted mass ordering
  (even for extremely small θ_{13})

Neutrino detection for SN astrophysics

- Pointing to the SN in advance
- Tracking SN shock wave in neutrinos
- Testing primary flux models

Scope of this talk

What this talk will contain

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

What this talk will stay away from

- The explosion mechanism and role of neutrinos

  Talk by Christian Ott

- Diffuse supernova neutrino flux

  Talks by Takashi Lida, Cecilia Lunardini

- Non-standard neutrino interactions

Outline

1. Neutrino production and detection
   - Neutrino emission and primary spectra
   - Detection of a galactic supernova
2. Neutrino propagation and flavor conversions
   - Matter effects inside the star: collective and MSW
   - Earth matter effects
   - Shock wave effects
3. Smoking gun signals
   - During neutronization burst
   - During the accretion and cooling phase
4. Concluding remarks

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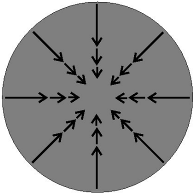
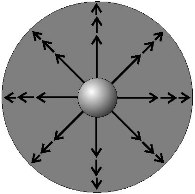
Core collapse, shock wave, and explosion

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* ???

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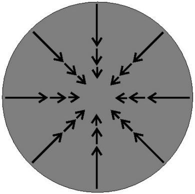

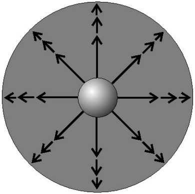

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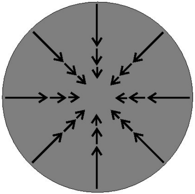

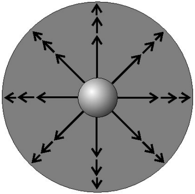

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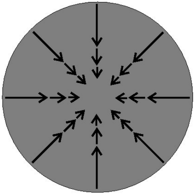

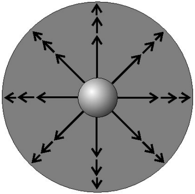

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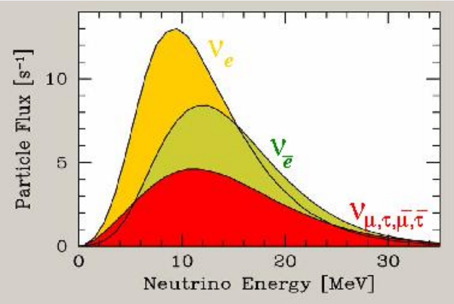
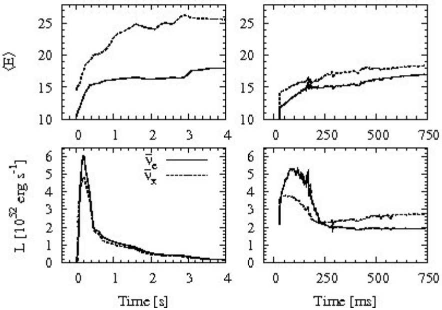
Primary fluxes and spectra



- Almost blackbody spectra, slightly "pinched"
- Energy hierarchy: $\langle E_0(\nu_e)\rangle < \langle E_0(\bar{\nu}_e)\rangle < \langle E_0(\nu_x)\rangle$
- $\langle E_0(\nu_e)\rangle \approx$ 10–12 MeV
  $\langle E_0(\bar{\nu}_e)\rangle \approx$ 13–16 MeV
  $\langle E_0(\nu_x)\rangle \approx$ 15–25 MeV

ν_x: any linear combination of ν_μ and ν_τ

Flavor-dependence of neutrino fluxes



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

Differing model predictions in cooling phase:

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)

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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:

- $\bar{\nu}_e p \rightarrow n e^+$ ($\sim$ 300 per kt)
- $\nu + {}^{12}C \rightarrow \nu + X + \gamma$ (15.11 MeV)

Liquid Argon detector:

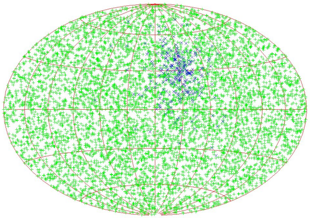
- $\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$ ($\sim$ 300 per kt)

Talks by Walter Fulgione, Alex Habig, Kate Scholberg

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).

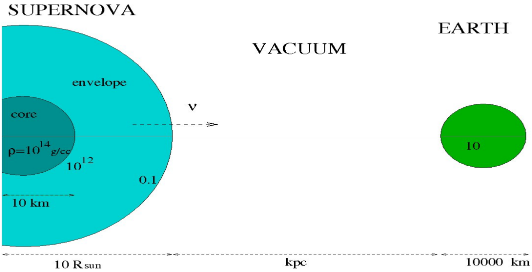
GADZOOKS

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

(Talks by Alex Habig, Kate Scholberg)

Outline

Propagation through matter of varying density



Inside the SN: *flavor conversion*

Collective effects and MSW matter effects

Between the SN and Earth: *no flavor conversion*

Mass eigenstates travel independently

Inside the Earth: *flavor oscillations*

MSW matter effects (*if detector is shadowed by the Earth*)

Outline

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

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

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

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

- $d\rho/dt = i[H(\rho), \rho] \quad \Rightarrow$ 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, PRL 97, 241101 (2006)

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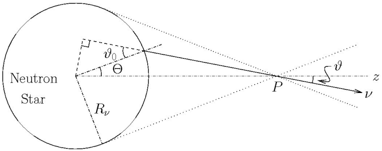
Multi-angle vs. single-angle approximation



H.Duan, G.M.Fuller, J.Carlson

Y.-Z. Qian, PRD74, 105014 (2006)

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

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

- "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)

- If matter density is sufficiently high (may be possible during the accretion phase), multi-angle decoherence possible.

A.Esteban-Pretel, A.Mirizzi, S.Pastor, R.Tomas, G.G. Raffelt,

P.D.Serpico, G. Sigl, PRD78, 085012 (2008)

Single-angle approximation used unless specified

"Collective" effects: qualitatively new phenomena

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 $\nu_e\bar{\nu}_e \leftrightarrow \nu_x\bar{\nu}_x$ oscillations in inverted hierarchy even for extremely small θ_{13}

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

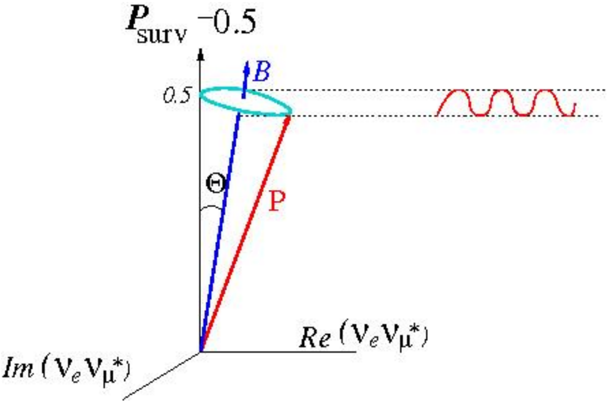
Spectral split:

ν_e and ν_x ($\bar{\nu}_e$ and $\bar{\nu}_x$) spectra interchange completely, only within certain energy ranges, depending on the mass ordering.

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

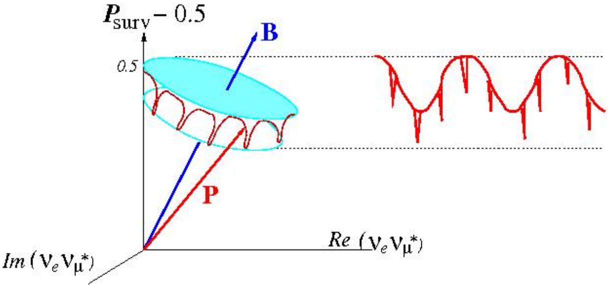
B. Dasgupta, AD, G.Raffelt, A.Smirnov, arXiv:0904.3542 [hep-ph], PRL

Synchronized oscillations



- $P = P_\nu - P_{\bar{\nu}}$
- ν and $\bar{\nu}$ of all energies oscillate with the same frequency
- No significant flavor change since mixing angle is small

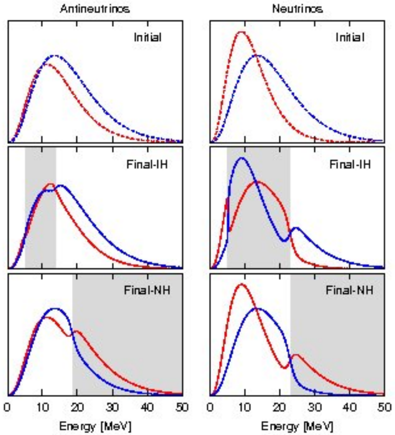
Bipolar oscillations



- Coherent $\nu_e \bar{\nu}_e \leftrightarrow \nu_x \bar{\nu}_x$ oscillations
- Take place even for $\theta_{13} \lesssim 10^{-10}$
- Analogous to a nutating top
- Prepare neutrinos for the "spectral split"

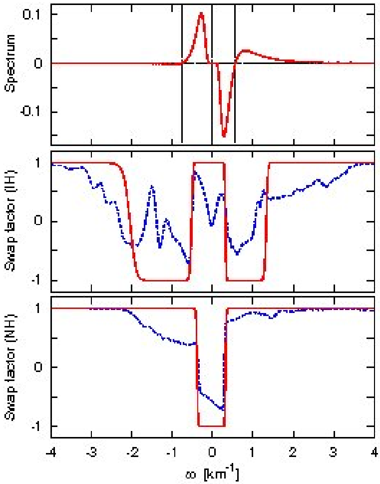
Spectral split

cooling-phase Garching fluxes



B. Dasgupta, AD, G.Raffelt, A.Smirnov, arXiv:0904.3542 [hep-ph], PRL

Spectral split in terms of "swaps"

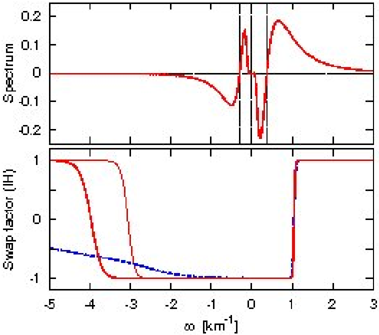


- Neutrinos:
  $\omega \equiv 1/E$
- Antineutrinos:
  $\omega \equiv -1/E$
- Spectrum
  $g(|\omega|) = F_{\nu_e}(\omega) - F_{\nu_x}(\omega)$
  $g(-|\omega|) = F_{\bar{\nu}_x}(\omega) - F_{\bar{\nu}_e}(\omega)$
- Swap
  $S(\omega) = \frac{g(\omega)_{final}}{g(\omega)_{initial}}$

Swap $S(\omega) = -1 \Rightarrow$

- Inverted Hierarchy: positive crossing
- Normal Hierarchy: negative crossing

Single spectral split for almost-hierarchical fluxes



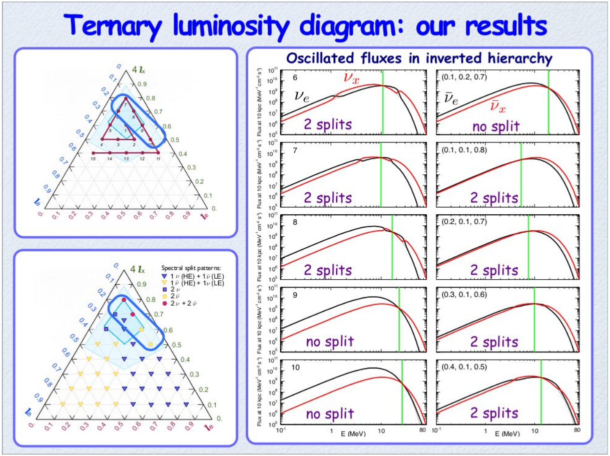
Early-time Garching

- $F^0_{\nu_e} > F^0_{\bar{\nu}_e} > F^0_{\nu_x} = F^0_{\bar{\nu}_x}$ at almost all energies
- $g(|\omega|) > 0$, $g(-|\omega|) < 0$
- Single visible split (Two close swaps)

- Antineutrino $S = -1$ always
  $\Rightarrow$ Antineutrino spectra completely swapped
- Neutrino $S = -1$ only for $\omega < \omega_{split}$
  $\Rightarrow$ Neutrino spectra swapped only for $E > E_{split}$

B. Dasgupta, AD, G.Raffelt, A.Smirnov, arXiv:0904.3542 [hep-ph], PRL

In general, the final answer is complicated



Talk by Irene Tamborra

Three-flavor collective effects

Three-flavor results by combining two-flavor ones

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

B.Dasgupta and AD, PRD77, 113002 (2008)

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*

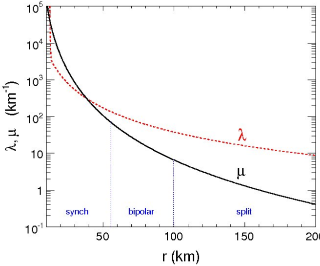
A.Esteban-Pretel, S.Pastor, R.Tomas, G.Raffelt, G.Sigl, PRD77, 065024 (2008)

- Spectral splits develop at two energies, in a stepwise process, during neutronization burst of a O-Ne-Mg SN.

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

B.Dasgupta, AD, A.Mirizzi and G. G. Raffelt, PRD77, 113007 (2008)

Sequential dominance of phenomena (Fe-core SN)



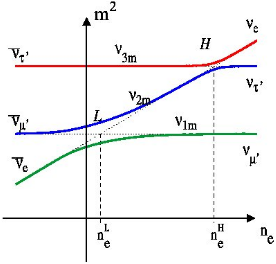
- $\mu \equiv \sqrt{2} G_F (N_\nu + N_{\bar{\nu}})$
- $\lambda \equiv \sqrt{2} G_F N_e$

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

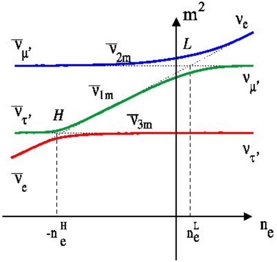
G.L.Fogli, E. Lisi, A. Marrone, A. Mirizzi, JCAP 0712, 010 (2007)

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:

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

Survival probabilities for almost-hierarchical fluxes (Livermore, early time Garching) AHF

	Hierarchy	$\sin^2\theta_{13}$	p	$\bar{p}$
A	Normal	Large	0	$\sin^2\theta_\odot$
B	Inverted	Large	$\cos^2\theta_\odot \,\|\|\, 0$	$\cos^2\theta_\odot$
C	Normal	Small	$\sin^2\theta_\odot$	$\cos^2\theta_\odot$
D	Inverted	Small	$\cos^2\theta_\odot \,\|\|\, 0$	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, PRD77, 113002 (2008)

Outline

Earth matter effects

- If F_{ν_1} and F_{ν_2} reach the earth,

$$F^D_{\nu_e}(L) - F^D_{\nu_e}(0) = (F_{\nu_2} - F_{\nu_1}) \times \sin 2\theta^{\oplus}_{12} \sin(2\theta^{\oplus}_{12} - 2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{\oplus} L}{4E}\right)$$

(Sign changes for antineutrinos)

- Nonzero Earth matter effects require
  - Neutrinos: $p \neq 0$
  - Antineutrinos: $\bar{p} \neq 0$

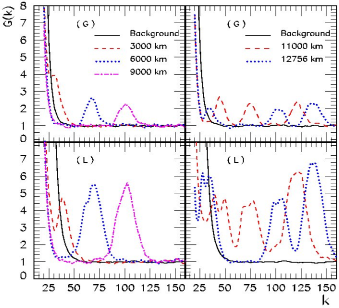
Presence or absence of Earth matter effects: AHF

	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

Earth effects: oscillations at a single detector

Fourier power spectrum: $G_N(k) = \frac{1}{N} \left| \sum_{events} e^{iky} \right|^2$
$(y \equiv 25\ MeV/E)$

- Peak positions model independent, at known frequencies



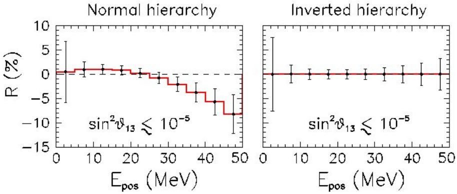
AD, M. Kachelrieß, G. Raffelt,
R. Tomàs, JCAP 0401:004 (2004)

Comparison between two detectors

- Ratio of luminosities at IceCube and a megaton water Cherenkov, as a function of time

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

- Comparing spectra at two megaton water Cherenkovs



$$R \equiv \frac{N_{shadowed} - N_{unshadowed}}{N_{unshadowed}}$$

B.Dasgupta, AD, A. Mirizzi, PRL101, 171801 (2008)

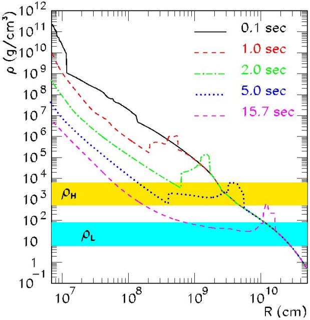
Robust experimental signature AHF

- Earth effects can distinguish hierarchies even for $\theta_{13} \lesssim 10^{-10}$

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
- 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)

Shock signals at a megaton water Cherenkov

- Dip/peak features in $\langle E_{\nu_e} \rangle$
- Double dip / double peak when forward + reverse shock

- Times at which dips/peaks appear in $F_{\bar{\nu}_e}(E)$ are the times at which the shock waves enter the densities

$$\rho(E) = \frac{m_N \Delta m^2_{atm}}{2\sqrt{2} G_F Y_e E}$$

- $\Rightarrow$ Tracking of shock wave while it is still inside the mantle

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

Combination with a gravitational wave signal will yield valuable information about explosion.

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Shock wave signals

Presence or absence of shock wave signal: AHF

	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

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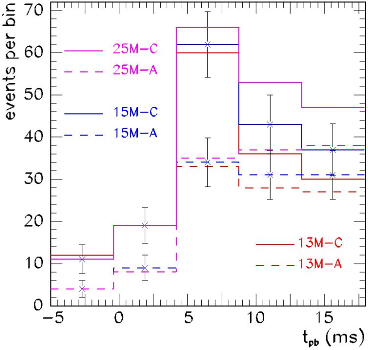
Vanishing ν_e burst



Automatically AHF

M. Kachelriess, R. Tomas, R. Buras,

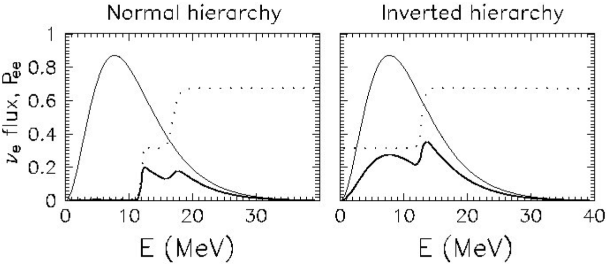
H. T. Janka, A. Marek and M. Rampp

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



Neutronization burst

automatically AHF

- MSW resonances deep inside collective regions

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

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

- “MSW-prepared” spectral splits: two for IH, one for NH

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, PRD77, 1130007 (2008)

- ν_e suppression much more at low energy
- Identification of O-Ne-Mg supernova ??

Outline

Identifying neutrino mixing scenario

Four distinguishable scenarios: $\boxed{\text{AHF}}$

	Hierarchy	$\sin^2\theta_{13}$	Survival probability p	Survival probability $\bar{p}$	Shock effects ν_e	Shock effects $\bar{\nu}_e$	Earth effects ν_e	Earth effects $\bar{\nu}_e$
A	Normal	$\gtrsim 10^{-3}$	0	$\cos^2\theta_\odot$	$\surd$	$\surd$	X	$\surd$
B	Inverted	$\gtrsim 10^{-3}$	$\cos^2\theta_\odot$ || 0	$\cos^2\theta_\odot$	X	$\surd$	X	$\surd$
C	Normal	$\lesssim 10^{-5}$	$\sin^2\theta_\odot$	$\cos^2\theta_\odot$	X	X	$\surd$	$\surd$
D	Inverted	$\lesssim 10^{-5}$	$\cos^2\theta_\odot$ || 0	0	X	X	X	X

- In principle, hierarchy can be identified even for extremely small θ_{13} values
- Robust signals exist:
  - 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, PRL101, 171801 (2008)

All this true if fluxes are AHF (early time simulations agree)

Outline

Concluding remarks

- Supernova neutrinos probe neutrino mass hierarchy and θ_{13} range, even for extremely small θ_{13}, 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
  - Tracking the shock wave while still inside mantle
  - Testing primary flux models
- Caveat emptor
  - Can multiple splits in non-AHF scenarios confound the identification of the mixing scenario ?
  - Can multi-angle decoherence, turbulent decoherence wipe away the signals ?

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What needs to be done

What the theorists should do

- More reliable predictions of primary fluxes
- Better understanding of the nonlinear collective effects
- Look for ways of solving the “Inverse SN neutrino problem”

What the experimentalists should do

- Do not believe the theorists
- Be prepared for surprises

What the speaker should do

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