Supernova neutrinos

A SmirnovFest overview

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SmirnovFest, Invisibles meeting
GGI Florence, June 28, 2012

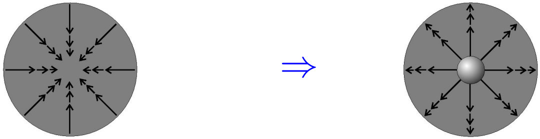
Outline

1. Supernova explosion: a 10-sec history
2. MSW-controlled flavor conversions
3. Collective flavor conversions
4. Neutrino signals at detectors

Outline

Core collapse, shock wave, neutrino emission

Gravitational core collapse $\Rightarrow$ Shock Wave



Neutrino emission: $\sim 10^{58}$ neutrinos

- Neutronization burst: ν_e emitted for $\sim$ 10 ms
- Accretion phase: Larger $\nu_e/\bar{\nu}_e$ luminosity
- Cooling through neutrino emission:
  all $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ with similar luminosities
- Energy $\sim 10^{53}$ erg emitted within $\sim$ 10 sec.

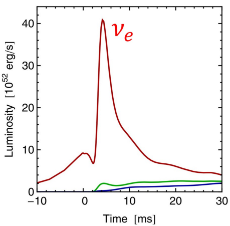
After neutrino emission

Explosion, via neutrino heating, hydrodynamic instabilities, etc.

Neutrino fluxes: luminosities

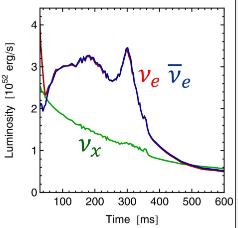
Three Phases of Neutrino Emission

Prompt ν_e burst



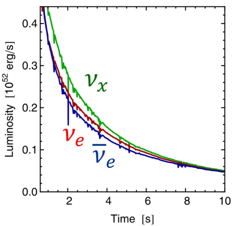
- Shock breakout
- De-leptonization of outer core layers

Accretion



- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling

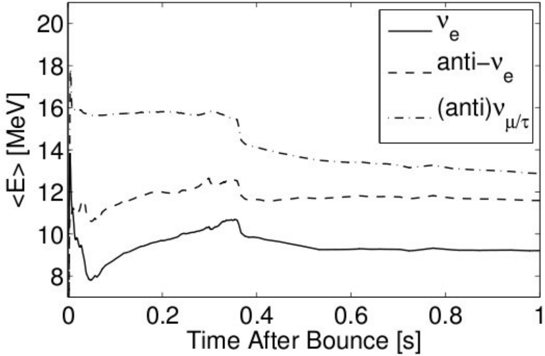


Cooling on neutrino diffusion time scale

- Spherically symmetric model (10.8 $M_\odot$) with Boltzmann neutrino transport
- Explosion manually triggered by enhanced CC interaction rate

Fischer et al. (Basel group), A&A 517:A80, 2010 [arxiv:0908.1871]

Neutrino fluxes: energy spectra

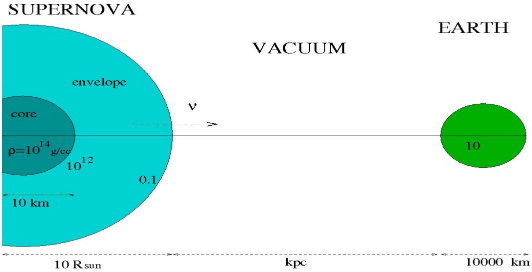


$10.8 M_{\odot}$ star

Fischer et al, arXiv:0908.1871

- Approximately thermal spectra
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau} \rangle$

Oscillations of SN neutrinos



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*)

Changing paradigm of supernova neutrino oscillations

MSW-dominated flavor conversions (pre-2006)

- Flavor conversions mainly in MSW resonance regions : ($\rho \sim 10^{3-4}$ g/cc, 1–10 g/cc)
- Non-adiabaticity, shock effects, earth matter effects
- Sensitivity to $\sin^2\theta_{13} \gtrsim 10^{-5}$ and mass hierarchy

Collective effects on neutrino conversions (post-2006)

- Significant flavor conversions due to ν–ν forward scaterring Near the neutrinosphere : ($\rho \sim 10^{6-10}$ g/cc)
- Synchronized osc $\rightarrow$ bipolar osc $\rightarrow$ spectral split
- Sensitivity to much smaller $\sin^2\theta_{13}$ than MSW effects

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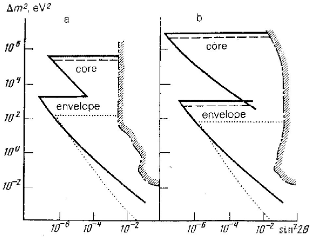
Outline

Before SN 1987A: resonances and adiabaticities

Neutrino oscillations in a variable-density medium and $\nu-$ bursts due to the gravitational collapse of stars

S. P. Mikheev and A. Yu. Smirnov
Institute of Nuclear Research, Academy of Sciences of the USSR
(Submitted 24 December 1985)
Zh. Eksp. Teor. Fiz. **91**, *7-13 (July 1986)*

Under certain conditions, the propagation of a beam of oscillating neutrinos in a variable-density medium takes the form of an almost complete transformation of the initial type of neutrino into another type. The depth of oscillations is then negligible. The transformation can occur in the cores and envelopes of collapsing stars.



- Two-neutrino mixing: $\nu_e \leftrightarrow \nu_\mu$, $\nu_e \leftrightarrow \nu_s$
- Regions of adiabatic ν conversions in the $(\Delta m^2, \sin^2 2\theta)$ plane

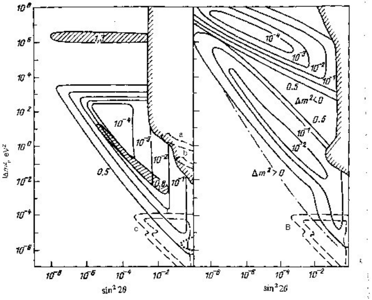
Exploiting SN 1987A: limits on mixing parameters

Resonant oscillations and limitations found on neutrino parameter values from the possible observation of a ν burst from the gravitational collapse of a star

S. P. Mikheev and A. Yu. Smirnov
Institute of Nuclear Research, Academy of Sciences of the USSR

(Submitted 21 May 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **46**, No. 1, 11-13 (10 July 1987)

Limitations on neutrino parameter values are found from the possible observation of a neutrino signal associated with the supernova SN1987A. Resonant oscillations are taken into account. The effect of the material of the earth is estimated.



- Limits on mixing parameters (2ν) from SN1987A observations
- Earth matter effects included

Exploiting SN 1987A: neutrino decay

MATTER-INDUCED NEUTRINO DECAY AND SUPERNOVA 1987A

Z.G. BEREZHIANI [a,1] and A.Yu. SMIRNOV [b]
[a] *Lebedev Physical Institute, Moscow 117 924, USSR*
[b] *Institute for Nuclear Research of the Academy of Sciences of the USSR, Moscow 117 312, USSR*

Received 7 January 1989

Due to coherent interaction with matter the neutrino could decay into an antineutrino and a majoron: $\nu \to \bar{\nu} + \varphi$ or vice versa, $\bar{\nu} \to \nu + \varphi$. The properties of this decay are analysed in some detail and the implications for the supernova explosion and accompanied neutrino burst are discussed. Using the data on the ν-signal from SN1987A the upper bound on the $\nu_e \nu_e \varphi$ interaction constant is obtained: $h < 10^{-6}$.

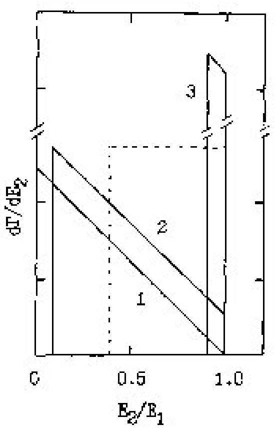


Fig. 1. The energy distributions of secondary neutrinos in matter-induced ν–$\bar{\nu}$ decay: the solid lines 1, 2, 3 correspond to the cases $\xi = 0$, $\xi \ll 1$ and $\xi \gg 1$, respectively ($\xi = m^2/2E_1 V$). For comparison the distribution for $\nu_1 \to \nu_2 + \varphi$ decay in vacuum is shown also (dotted line).

- Neutrino decay to antineutrino and Majoron in presence of matter
- Limits on $\nu_e \nu_e \phi$ coupling obtained

After neutrino oscillations were confirmed: 3ν analysis

PHYSICAL REVIEW D, VOLUME 62, 033007

Identifying the neutrino mass spectrum from a supernova neutrino burst

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The Abdus Salam International Center for Theoretical Physics, 34100 Trieste, Italy
and Institute of Nuclear Research, RAS, Moscow, Russia
(Received 31 January 2000; published 12 July 2000)

We study the role that the future detection of the neutrino burst from a galactic supernova can play in the reconstruction of the neutrino mass spectrum. We consider all possible 3ν mass and flavor spectra which describe the solar and atmospheric neutrino data. For each of these spectra we find the observable effects of the supernova neutrino conversions both in the matter of the star and the Earth. We show that studies of the electron neutrino and antineutrino spectra as well as observations of the neutral current effects from supernova will allow us (i) to identify the solar neutrino solution, (ii) to determine the type of mass hierarchy (normal or inverted) and (iii) to probe the mixing $|U_{e3}|^2$ to values as low as $10^{-4}-10^{-3}$.

SN neutrino signal is sensitive to mass hierarchy and θ_{13}

Linea deviata: a SmirnovFest aside

Confessions of an (ex-)reluctant neutrino physicist

- Low-energy collider physicist, no intentions of working on neutrinos, did not believe in neutrino mass
- Started working in neutrinos only after the SK zenith angle results in 1998
- SN neutrinos: too many cases since solar neutrino solution and θ_{13} unknown, and we may not need it for a few decades anyway.
- Alexei's words: let us write a paper that people will use for the next 30 years

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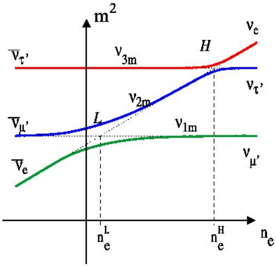
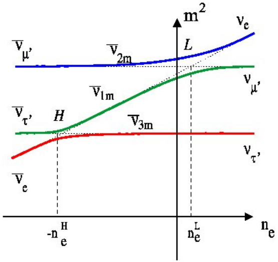
MSW Resonances inside a SN

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

Survival probabiities p and $\bar{p}$

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

- Approx constant with energy for "small" θ_{13} ($\sin^2\theta_{13} \lesssim 10^{-5}$) and "large" θ_{13} ($\sin^2\theta_{13} \gtrsim 10^{-3}$)
- Unless the primary fluxes have widely different energies, it is virtually impossible to determine p or $\bar{p}$ given a final spectrum
- Zero / nonzero values of p or $\bar{p}$ can be determined through indirect means (earth matter effects)

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)

- $p = 0 \Rightarrow F_{\nu_1} = F_{\nu_2}$, $\bar{p} = 0 \Rightarrow F_{\bar{\nu}_1} = F_{\bar{\nu}_2}$
- Nonzero Earth matter effects require
  - Neutrinos: $p \neq 0$
  - Antineutrinos: $\bar{p} \neq 0$
- Possible to detect Earth effects since they involve oscillatory modulation of the spectra
- An indirect way of determining nonzero p or $\bar{p}$

Predictions for different mixing scenarios

Solar neutrino solution

SMA / LMA / VO

$\otimes$

Value of $\sin^2 \theta_{13}$

less than 10^{-5} / between 10^{-5} and 10^{-3} / greater than 10^{-3}

$\otimes$

Mass hierarchy

Normal / inverted

SN 1987A flux parameters with LMA

Neutrinos from SN 1987A, Earth matter effects, and the large mixing angle solution of the solar neutrino problem

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and INFN, sezione di Trieste, via Valerio 2, 34127 Trieste, Italy

A. Yu. Smirnov
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and Institute for Nuclear Research, RAS, Moscow, Russia
(Received 25 October 2000; published 7 March 2001)

We study the properties of the oscillation effects in the matter of the Earth on antineutrino fluxes from supernovae. We show that these effects can provide an explanation of the difference in the energy spectra of the events detected by Kamiokande-2 and IMB detectors from SN 1987A as well as the absence of high-energy events with $E \gtrsim 40$ MeV. This explanation requires the neutrino oscillation parameters Δm^2 and $\sin^2 2\theta$ to be in the region of the large mixing angle solution of the solar neutrino problem and the normal mass hierarchy if $|U_{e3}|^2 \gtrsim 10^{-3}$. The hierarchy can be inverted if $|U_{e3}|^2 \lessdot 10^{-3}$. The solution of the solar neutrino problem based on ν_e conversion to a pure sterile state is disfavored by SN 1987A data.

Combined analysis of K2 and IMB data

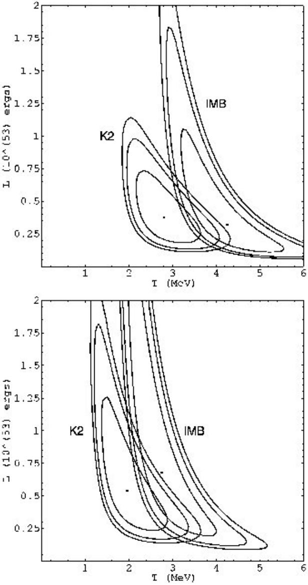
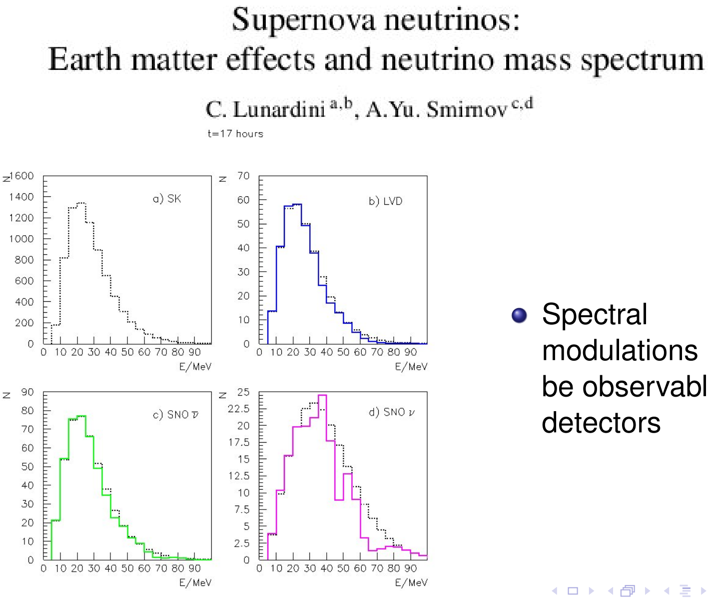


FIG. 4. Best fit points and contours of equal 68, 90, 95.4 % likelihood for K2 and IMB detectors in the $T_{\bar{\nu}_e}$-$L_{\bar{\nu}_e}$ plane. The upper panel shows the result of the separate fits of K2 and IMB data without oscillation effects. The lower panel represents a similar fit in presence of oscillations. The following values for the oscillation parameters and characteristics of original spectra have been used: $T_{\bar{\nu}_\mu'}/T_{\bar{\nu}_e}=1.8$, $L_{\bar{\nu}_\mu'}/L_{\bar{\nu}_e}=1$, $\eta_{\bar{e}}=\eta_{\bar{\mu}'}=0$ and $\cos 2\theta=0.2$, $\Delta m^2=3\times10^{-5}$ eV^2.

- Comparison of $(T_{\bar{\nu}_e}, L_{\bar{\nu}_e})$ favored by observations at two detectors
- LMA $\oplus$ earth matter effects makes the two observations more consistent.

Earth matter effects on spectra at detectors

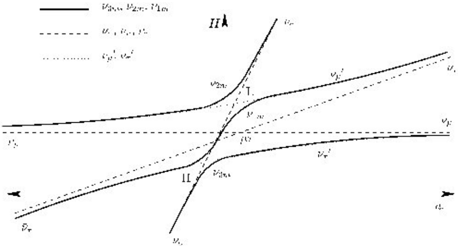


- Spectral modulations may be observable at detectors

Effect of a difference in ν_μ and ν_τ fluxes

Supernova neutrinos: difference of ν_μ–ν_τ fluxes and conversion effects

Evgeny Kh. Akhmedov [a,1], Cecilia Lunardini [b],
Alexei Yu. Smirnov [c,d]

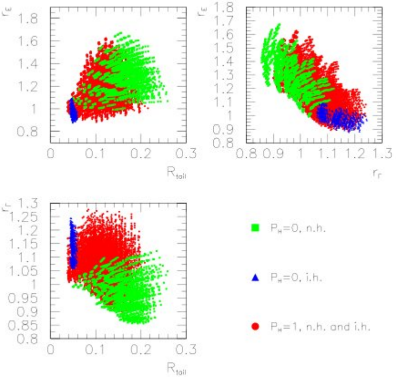


- Effective ν_μ-ν_τ potential
- Survival prob. at high energies ($E \gtrsim 50$ GeV) affected

Mass hierarchy and θ_{13} from SN ν spectra

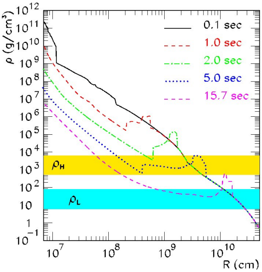
Probing the neutrino mass hierarchy and the 13-mixing with supernovae

Cecilia Lunardini[1,2] and Alexei Yu Smirnov[3,4]



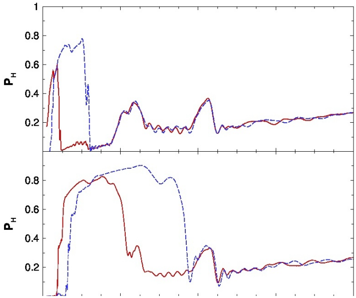
- Distinguishing among neutrino mixing scenarios
- Uncertainties in the primary spectra (and as now we know, collective effects) make things difficult

Shock wave imprint on neutrino spectra



- When shock wave passes through a resonance region, adiabaticity may be momentarily lost
- Sharp, time-dependent changes in the neutrino spectra

Schirato and Fuller, astro-ph/0205390, Fogli et al., PRD 68, 033005 (2003)



$t = 2, 2.5, 3, 3.5$ sec

- With time, resonant energies increase
- Possible in principle to track the shock wave to some extent

Tomas et al., JCAP 0409, 015 (2004)

Kneller et al., PRD 77, 045023 (2008)

Turbulence

- Turbulent convections behind the shock wave ⇒ gradual depolarization effects
- 3-flavor depolarization would imply equal fluxes for all flavors ⇒ No oscillations observable

Friedland, Gruzinov, astro-ph/0607244; Choubey, Harries, Ross, PRD76, 073013 (2007)

- For "small" amplitude, turbulence effectively two-flavor
- For large θ_{13}, shock effects likely to survive
- Jury still out

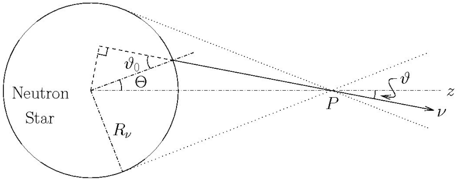
Kneller and Volpe, PRD 82, 123004 (2010)

Outline

Single-angle approximation

- Effective Hamiltonian: $H = H_{vac} + H_{MSW} + H_{\nu\nu}$

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



Duan, Fuller, Carlson, Qian, PRD 2006

Single-angle: All neutrinos face the same average $\nu\nu$ potential [effective averaging of $(1 - \cos\theta_{pq})$]

“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/pendular oscillations:

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

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

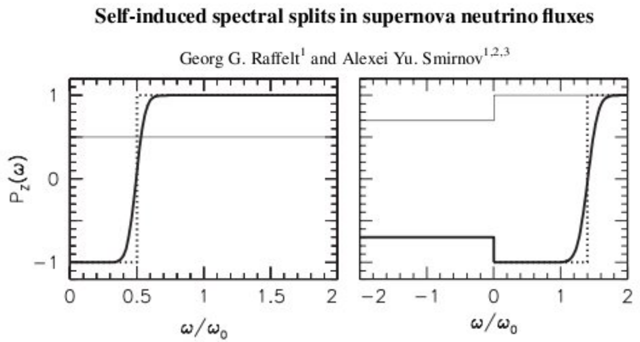
Spectral split/swap:

ν_e and ν_x ($\bar{\nu}_e$ and $\bar{\nu}_x$) spectra interchange completely,
but only within certain energy ranges.

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

B. Dasgupta, AD, G.Raffelt, A.Smirnov, PRL103,051105 (2009)

"Classic" single spectral split



In inverted hierarchy

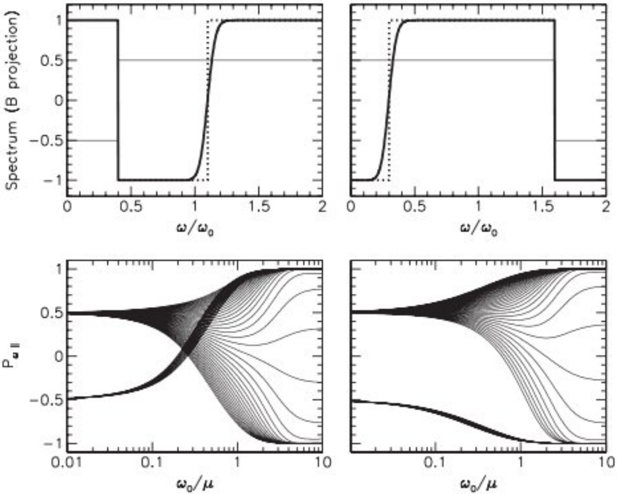
- All antineutrinos ($\omega < 0$) and neutrinos with $E > E_c$ "swap" flavors ($\nu_e \leftrightarrow \nu_\mu$, $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$)

Adiabaticity in classic spectral split

PHYSICAL REVIEW D **76**, 125008 (2007)

Adiabaticity and spectral splits in collective neutrino transformations

Georg G. Raffelt[1] and Alexei Yu. Smirnov[2,3]

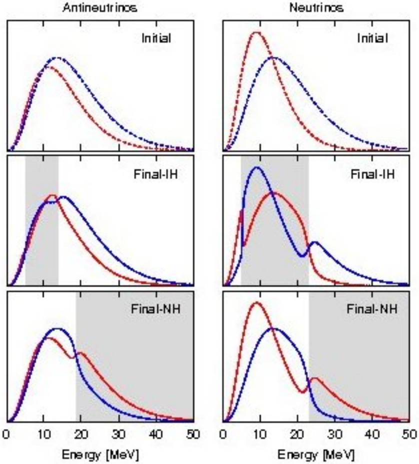


Multiple spectral splits

PRL **103,** 051105 (2009) PHYSICAL REVIEW LETTERS week ending 31 JULY 2009

Multiple Spectral Splits of Supernova Neutrinos

Basudeb Dasgupta,[1] Amol Dighe,[2] Georg G. Raffelt,[1] and Alexei Yu. Smirnov[3,4]



- Spectral splits as boundaries of swap regions
- Splits possible both for ν_e and $\bar{\nu}_e$
- Split positions depend on NH/IH

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

Problems and open questions in collective effects

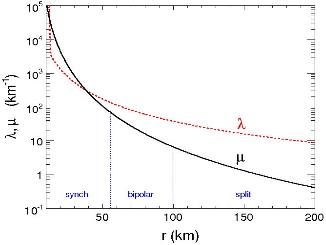
- Non-linear new effects: how to understand/model in terms of other known phenomena ?
- How good is the single-angle approximation ? Multi-angle effects seem to suppress collective effects, or make them appear earlier / later, or smoothen out their effects on the spectra.
- Normal matter at high densities also seems to give rise to additional suppression
- What will be the net effect of collective effects and matter effects ?

Talk by Georg Raffelt

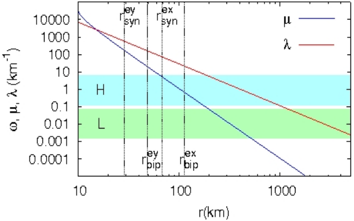
Outline

Sequential dominance of collective effects (Fe core)

Two-flavor



Three-flavor



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

- Regions of synchronized oscillations, bipolar oscillations, spectral split and MSW effects are well-separated.

Fogli, Lisi, Marrone, Mirizzi, JCAP 0712, 010 (2007), B.Dasgupta and AD, PRD77, 113002 (2008)

- The post-collective fluxes may be taken as "primary" ones on which the MSW-dominance analysis may be applied.
- In particular, shock-effect and earth-effect analyses remain unchanged.

Major reactions at the large detectors (SN at 10 kpc)

Water Cherenkov detector: (events at SK)

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

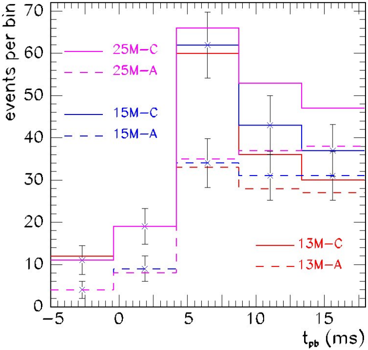
Carbon-based scintillation detector:

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

Liquid Argon detector:

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

Vanishing neutronization (ν_e) burst



- Flux during the neutronization burst well-predicted ("standard candle")

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

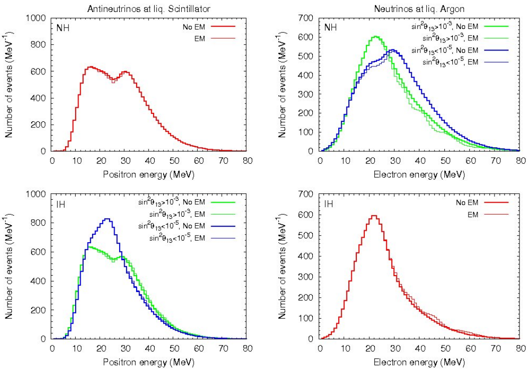
  H. T. Janka, A. Marek and M. Rampp

  PRD **71**, 063003 (2005)

Mass hierarchy identification (now that θ_{13} is large)

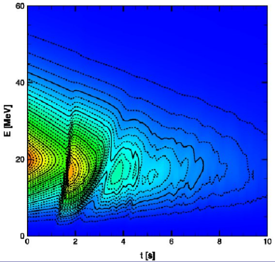
- Burst in CC suppressed by $\sim \sin^2\theta_{13} \approx 0.025$ for NH, only by $\sim \sin^2\theta_{12} \approx 0.3$ for IH
- Time resolution of the detector crucial for separating ν_e burst from the accretion phase signal

Earth matter effects



- Spectral split may be visible as “shoulders”
- Earth effects possibly visible, more prominent in ν_e
- Detection through spectral modulation, or comparison between time-dependent luminosities at large detectors.
- Only identify nonzero $p/\bar{p}$. Connecting to mass hierarchy requires better understanding of collective effects.

Shock wave effects



2D simulation
Positron spectrum
(inverse beta reaction)

Kneller et al., PRD77, 045023 (2008)

Observable shock signals

Time-dependent dip/peak features in $N_{\nu_e,\bar{\nu}_e}(E)$, $\langle E_{\nu_e,\bar{\nu}_e} \rangle$, ...

R.Tomas et al., JCAP **0409**, 015 (2004), Gava, et al., PRL 103, 071101 (2009)

Identifying mixing scenario: independent of collective effects

- Shock effects present in ν_e only for NH
- Shock effects present in $\bar{\nu}_e$ only for IH
- Absence of shock effects gives no concrete signal.
  primary spectra too close ? turbulence ?

Now that θ_{13} is measured to be large:

What about mass hierarchy ?

- Neutronization burst suppression / non-suppression (if we have an argon detector) is a sureshot signal.
- Shock wave effects, if positively identified (this may need a bit of luck in addition), will be a direct indication of MH.
- Collective effects would not affect these analyses.

Getting MH is not enough ! What about SN astrophysics ?

- The information in neutrino signal is much more than the 1-bit information about MH !
- Primary fluxes, density profiles, shock wave propagation.. a plethora of astrophysical information is out there.
- For extracting this information from the neutrino signal, a better understanding of collective effects is essential !

See talk by Georg Raffelt.

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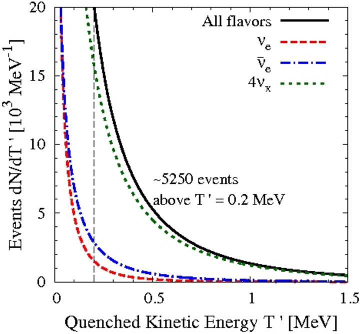
Live long and prosper

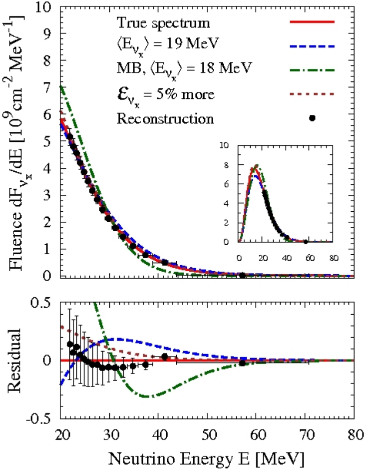
A.Yu.S-man bhava

Extra slides

NC events at a scintillator

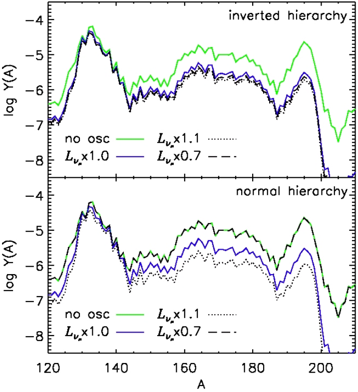


Detection of Very low energy protons from $\nu p \to \nu p \Rightarrow$ ν_μ spectrum reconstruction



Dasgupta and Beacom, PRD 83, 113006 (2011)

R-process nucleosynthesis

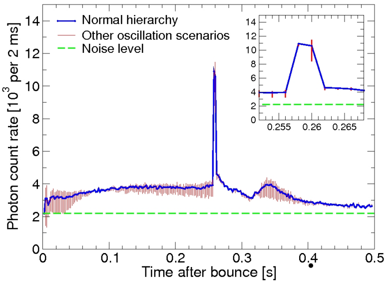


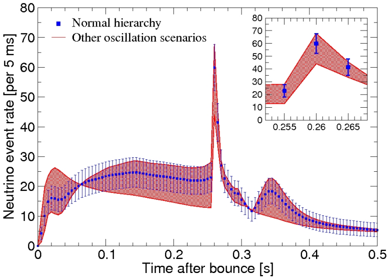
- Significant suppression effect in IH
- NH effects highly dependent on flux ratios
- Magnitude of effect dependent on astrophysical conditions

Duan, Friedland, McLaughlin, Surman, J. Phys. G: Nucl Part Phys, 38 , 035201 (2011)

QCD phase transition

- Sudden compactification of the progenitor core during the QCD phase transition
- Prominent burst of $\bar{\nu}_e$, visible at IceCube and SK

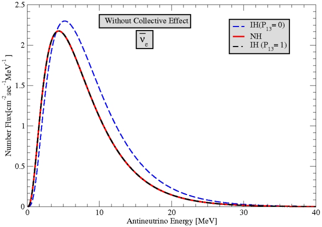


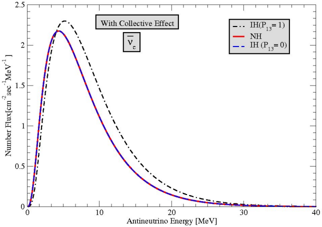


Dasgupta et al, PRD 81, 103005 (2010)

Diffused SN neutrino background

- Collective effects affect predictions of the predicted fluxes by up to $\sim 50\%$





Chakraborty, Choubey, Dasgupta, Kar, JCAP 0809, 013 (2009)

- Shock wave effects can further change predictions by $10 - 20\%$

Galais, Kneller, Volpe, Gava, PRD 81, 053002 (2010)