Supernova neutrino oscillations

Some new insights

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Current understanding of neutrino mixing

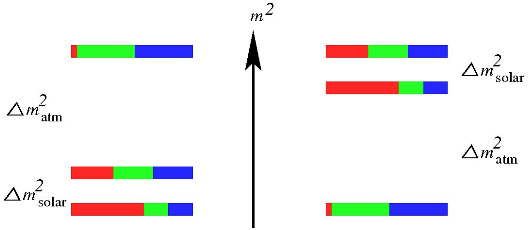
ν_e, ν_μ, ν_τ mix to form
three mass eigenstates ν_1, ν_2, ν_3

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

	Best fit	3σ range
$m_2^2 - m_1^2$ $[10^{-5}\mathrm{eV}^2]$	7.65	7.05 - 8.34
$\lvert m_3^2 - m_1^2 \rvert$ $[10^{-3}\mathrm{eV}^2]$	2.40	2.07 - 2.75
$\sin^2\theta_{12}$	0.304	0.25 - 0.37
$\sin^2\theta_{23}$	0.50	0.36 - 0.67
$\sin^2\theta_{13}$	0.01	$\leq$ 0.056

Mixing parameters relevant for SN neutrinos

Mixing of ν_e, ν_μ, ν_τ $\Rightarrow$ ν_1, ν_2, ν_3 (mass eigenstates)



- Mass ordering: Normal or Inverted ?
- Value of θ_{13}: how small ?
- Is there leptonic CP violation ?

Outline

1. Neutrino emission and primary spectra
2. Flavor conversions inside the star
   - Collective effects and spectral swaps
   - MSW resonances inside the star
   - Predicting swapped and unswapped regimes
3. Observable signals at the Earth
   - Earth matter effects
   - Shock wave effects
   - Neutronization burst signal
4. Inverse SN neutrino problem

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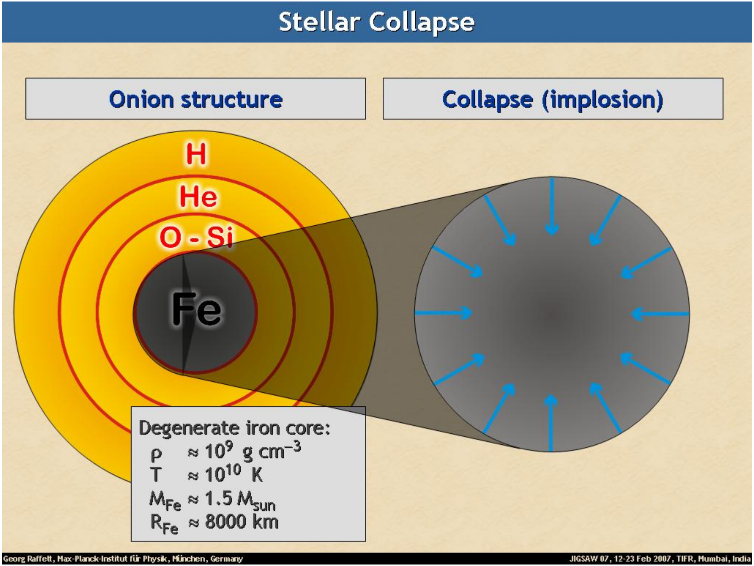
The would-be supernova before the collapse



Stellar Collapse

Onion structure

Collapse (implosion)

Degenerate iron core:

$\rho \approx 10^{9}\ \mathrm{g\ cm^{-3}}$

$T \approx 10^{10}\ \mathrm{K}$

$M_{Fe} \approx 1.5\ M_{sun}$

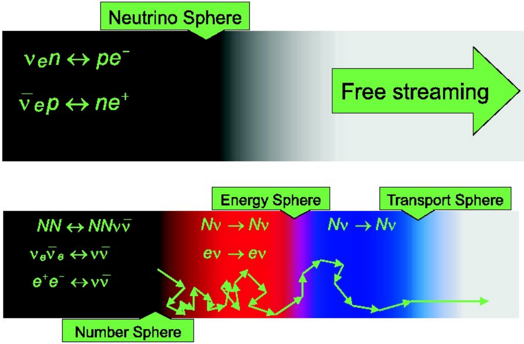
$R_{Fe} \approx 8000\ \mathrm{km}$

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

JIGSAW 07, 12-23 Feb 2007, TIFR, Mumbai, India

Trapped neutrinos before the collapse

- Neutrinos trapped inside “neutrinospheres” around $\rho \sim 10^{10}$g/cc
- Free-streaming when $\rho \lesssim 10^{10}$g/cc



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

$\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$

Core collapse, shock wave, and explosion

Gravitational core collapse ⇒ Shock Wave

Neutronization burst: ν_e emitted for $\sim$ 10 ms

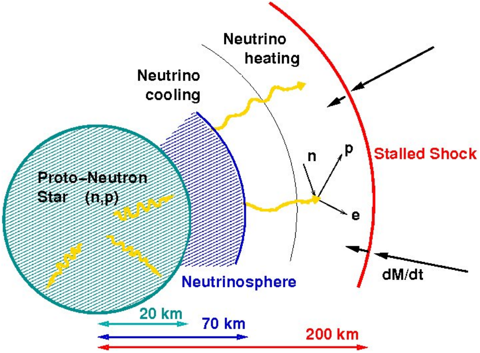
Cooling through neutrino emission: $\sim 10^{58}$ neutrinos

$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ Duration: About 10 sec

Emission of 99% of the SN collapse energy in neutrinos

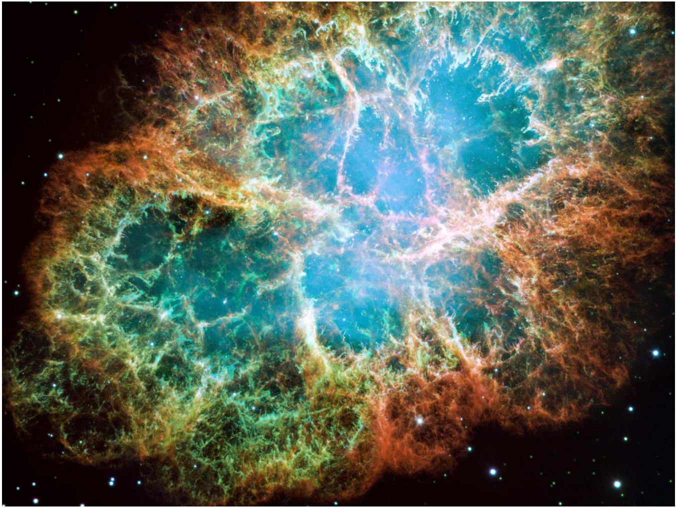
¿¿¿ Explosion ???

Role of neutrinos in explosion



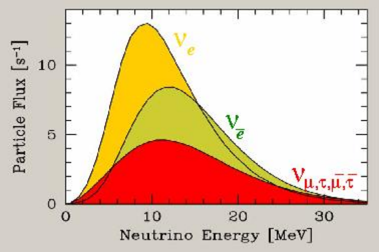
- Neutrino heating needed for pushing the shock wave
- Large scale convection also needed for explosion

The star after explosion



(Crab nebula, supernova seen in 1054)

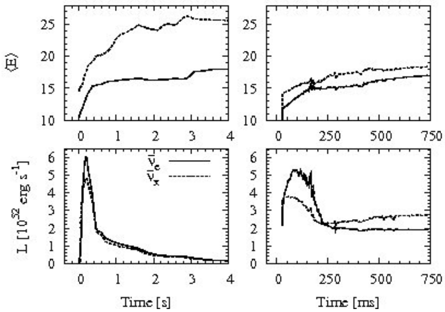
Primary fluxes and spectra



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

$$\boxed{\nu_x \equiv \cos\theta_{23}\nu_\mu - \sin\theta_{23}\nu_\tau, \quad \nu_y \equiv \sin\theta_{23}\nu_\mu + \cos\theta_{23}\nu_\tau}$$

Time-dependence, Flavor-dependence, Model-dependence



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	0.85	0.75
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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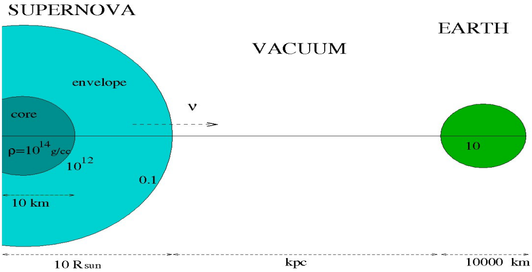
Propagation through matter of varying density



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*)

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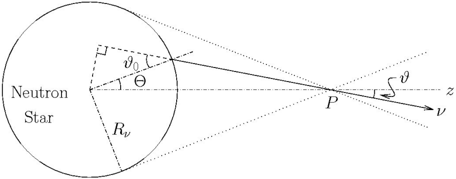
Nonlinear effects due to $\nu - \nu$ coherent interactions

- Large neutrino density ⇒ substantial ν–ν potential

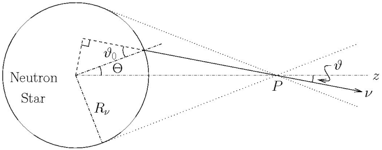
$$H = H_{vac} + H_{MSW} + H_{\nu\nu}$$

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

- $d\rho/dt = i[H(\rho), \rho]$ ⇒ Nonlinear effects !



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

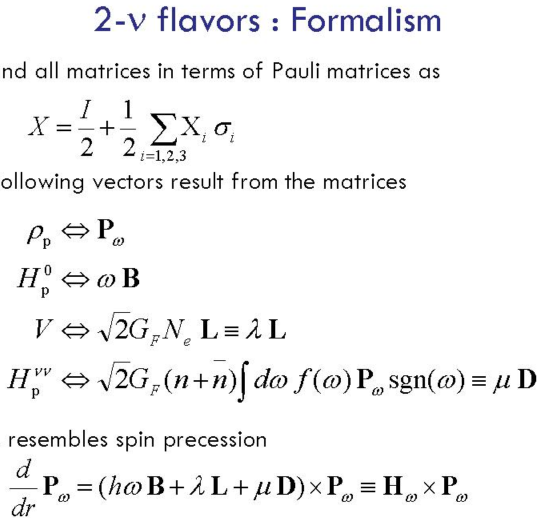
A.Esteban-Pretel, S.Pastor, R.Tomas, G.Raffelt, G.Sigl, PRD76, 125018 (2007)

- 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

Polarization-vector formalism



2-ν flavors : Formalism

- Expand all matrices in terms of Pauli matrices as

$$X = \frac{I}{2} + \frac{1}{2} \sum_{i=1,2,3} \mathrm{X}_i \, \sigma_i$$

- The following vectors result from the matrices

$$\rho_{\mathrm{p}} \Leftrightarrow \mathbf{P}_\omega$$

$$H_{\mathrm{p}}^{0} \Leftrightarrow \omega \, \mathbf{B}$$

$$V \Leftrightarrow \sqrt{2} G_F N_e \, \mathbf{L} \equiv \lambda \, \mathbf{L}$$

$$H_{\mathrm{p}}^{\nu\nu} \Leftrightarrow \sqrt{2} G_F (n + \bar{n}) \int d\omega \, f(\omega) \, \mathbf{P}_\omega \, \mathrm{sgn}(\omega) \equiv \mu \, \mathbf{D}$$

- EOM resembles spin precession

$$\frac{d}{dr} \mathbf{P}_\omega = (h\omega \, \mathbf{B} + \lambda \, \mathbf{L} + \mu \, \mathbf{D}) \times \mathbf{P}_\omega \equiv \mathbf{H}_\omega \times \mathbf{P}_\omega$$

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)

"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:

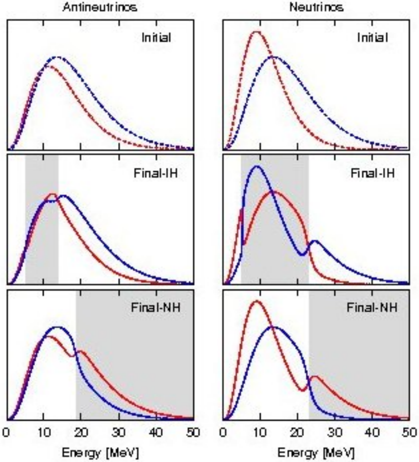
ν_e and ν_y ($\bar{\nu}_e$ and $\bar{\nu}_y$) spectra interchange completely, only within certain energy ranges.

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

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

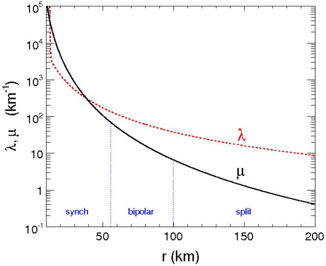
Spectral split/swap

cooling-phase Garching fluxes



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

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)

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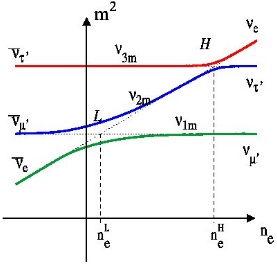
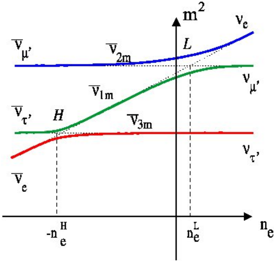
MSW Resonances inside a SN

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

Fluxes arriving at the Earth

Mixture of initial fluxes:

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

p and $\bar{p}$ in the swapped and unswapped energy regimes

		Θ_{13}	p unswapped	p swapped	$\bar{p}$ unswapped	$\bar{p}$ swapped
A	NH	Large	0	$\sin^2\theta_{12}$	$\cos^2\theta_{12}$	0
B	IH	Large	$\sin^2\theta_{12}$	0	0	$\cos^2\theta_{12}$
C	NH	small	$\sin^2\theta_{12}$	0	$\cos^2\theta_{12}$	0
D	IH	small	$\sin^2\theta_{12}$	0	$\cos^2\theta_{12}$	0

- “Small”: $\sin^2\theta_{13} \lesssim 10^{-5}$, “Large”: $\sin^2\theta_{13} \gtrsim 10^{-3}$.

AD, TAUP09 Talk

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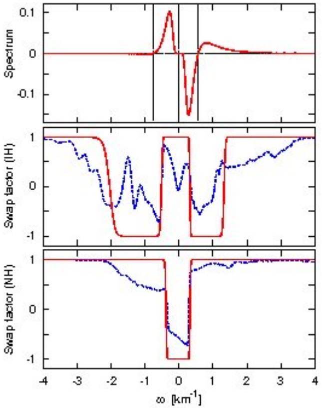
Mass ordering, specral crossings, swaps, and splits



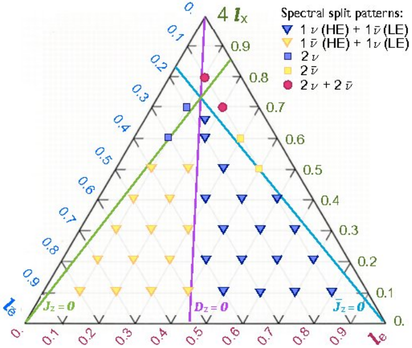
- Neutrinos:
  $\omega \equiv 1/E$
- Antineutrinos:
  $\omega \equiv -1/E$
- Spectrum
  $g(|\omega|) = F_{\nu_e}(\omega) - F_{\nu_x}(\omega)$
  $g(-|\omega|) = F_{\bar{\nu}_x}(\omega) - F_{\bar{\nu}_e}(\omega)$
- Swap
  $S(\omega) = \frac{g(\omega)_{final}}{g(\omega)_{initial}}$

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

- Inverted Hierarchy: positive crossing
- Normal Hierarchy: negative crossing
- Nearby swaps may overlap to reduce number of splits

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

In general, the final answer is complicated

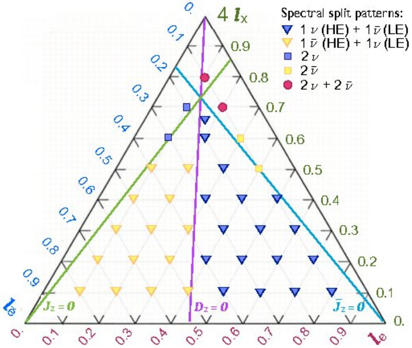


(Inverted hierarchy)

G.Fogli, E.Lisi, A.Marrone, I.Tamborra, JCAP 0910:002 (2009)

Is there a pattern ?

In general, the final answer is complicated

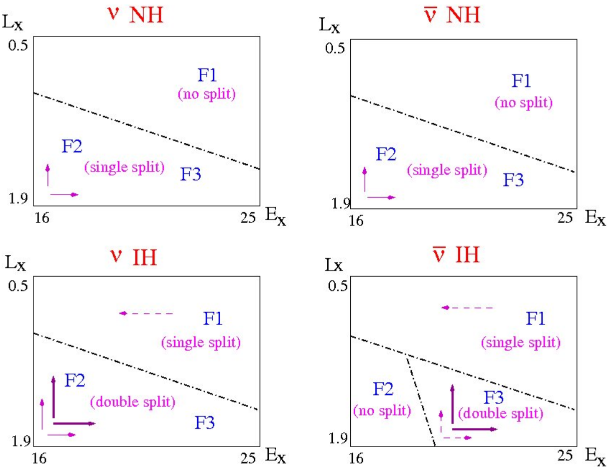


(Inverted hierarchy)

G.Fogli, E.Lisi, A.Marrone, I.Tamborra, JCAP 0910:002 (2009)

Is there a pattern ?

“Phase diagrams” of spectral splits



$$\boxed{\langle E_0(\nu_e)\rangle = 12\text{ MeV},\ \langle E_0(\bar\nu_e)\rangle = 15\text{ MeV},\ L_{\nu_e} = L_{\bar\nu_e} = 1.0}$$

S.Choubey, B.Dasgupta, AD, A. Mirizzi, *Work in Progress*

Survival probabilities with flux-mixing combinations

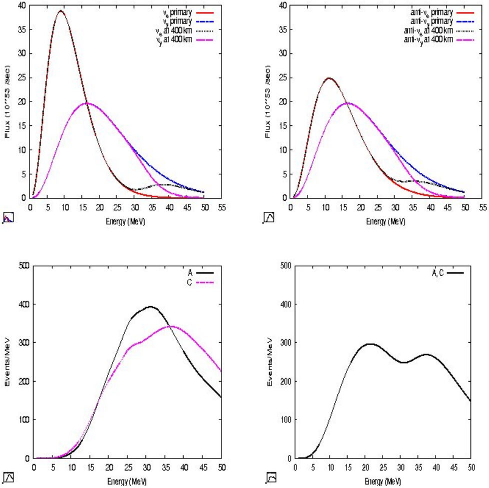
p at low, intermediate, high energies

	F_1			F_2			F_3		
A	0	0	0	0	0	s^2	0	0	s^2
B	s^2	0	0	s^2	0	s^2	s^2	0	s^2
C	s^2	s^2	s^2	s^2	s^2	0	s^2	s^2	0
D	s^2	0	0	s^2	0	s^2	s^2	0	s^2

$\bar{p}$ at low, intermediate, high energies

	F_1			F_2			F_3		
A	c^2	c^2	c^2	c^2	c^2	0	c^2	c^2	0
B	0	c^2	c^2	0	0	0	0	c^2	0
C	c^2	c^2	c^2	c^2	c^2	0	c^2	c^2	0
D	c^2	0	0	c^2	c^2	c^2	c^2	0	c^2

ν_e and $\bar{\nu}_e$ spectra at detectors



F3

$$\langle E_0(\nu_e)\rangle = 12\text{ MeV}$$
$$\langle E_0(\bar{\nu}_e)\rangle = 15\text{ MeV}$$
$$\langle E_0(\nu_y)\rangle = 22\text{ MeV}$$
$$L_{\bar{\nu}_e} = L_{\nu_e}$$
$$L_{\nu_y} = L_{\bar{\nu}_y} = 1.7 L_{\nu_e}$$

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A recent nearby supernova: 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)

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Earth matter effects

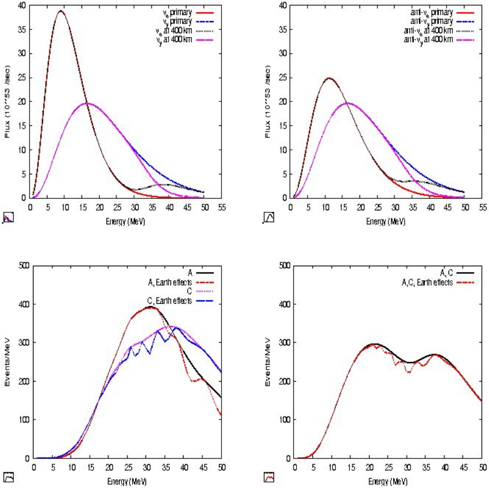
- If F_{ν_1} and F_{ν_2} reach the earth,

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

(Sign changes for antineutrinos)

- Nonzero Earth matter effects require
  - Neutrinos: $p \neq 0$
  - Antineutrinos: $\bar{p} \neq 0$
- Can distinguish scenarios depending on Earth effects in different energy regimes
- A more efficient way of detecting split positions

Spectra at detectors with Earth effects



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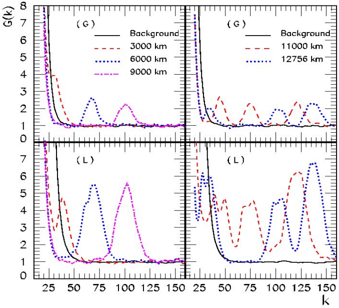
$$L_{\bar{\nu}_e} = L_{\nu_e}$$
$$L_{\nu_y} = L_{\bar{\nu}_y} = 1.7 L_{\nu_e}$$

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,

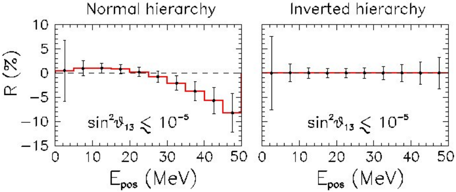
R. Tomàs, JCAP 0401:004 (2004)

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



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

$\boxed{\text{F1}}$. F2 and F3: NH ↔ IH

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

Robust experimental signature

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

Outline

1. Neutrino emission and primary spectra

2. Flavor conversions inside the star
   - Collective effects and spectral swaps
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3. Observable signals at the Earth
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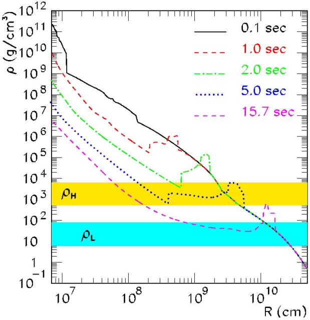
Shock wave and adiabaticity breaking

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

- Time-dependent dip/peak features in $N_{\nu_e,\bar{\nu}_e}(E)$, $\langle E_{\nu_e,\bar{\nu}_e}\rangle$, $\langle E^2_{\nu_e,\bar{\nu}_e}\rangle$, etc.
- Times at which dips/peaks appear in $N_{\bar{\nu}_e}(E)$ 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)

Identifying mixing scenario

- Shock wave present in ν_e only for scenario A
- Shock wave present in $\bar{\nu}_e$ only for scenario B

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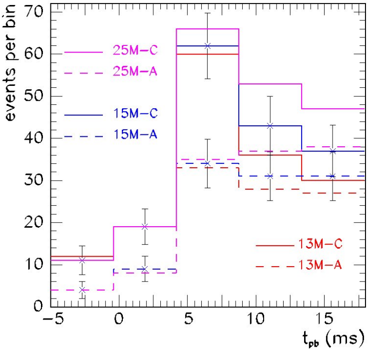
Vanishing ν_e burst



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

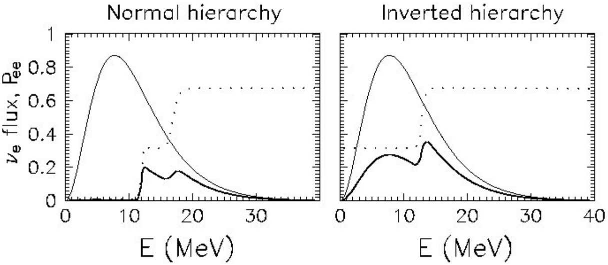
H. T. Janka, A. Marek and M. Rampp

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



Neutronization burst

- 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 ??

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Identifying neutrino mixing scenario

Multiple independent signals

	Earth Matter Effects				Shock effects		ν_e burst vanishing	Harder spectrum
	ν_e		$\bar{\nu}_e$		ν_e	$\bar{\nu}_e$		
	Peak	Tail	Peak	Tail				
AF1	X	X	√	√	√	X	√	ν_e
AF2	X	√	√	X	√	X	√	$\bar{\nu}_e$
AF3	X	√	√	X	√	X	√	$\bar{\nu}_e$
BF1	X	X	√	√	X	√	X	ν_e
BF2	X	√	X	X	X	√	X	$\bar{\nu}_e$
BF3	X	√	√	X	X	√	X	$\bar{\nu}_e$
CF1	√	√	√	√	X	X	X	?
CF2	√	X	√	X	X	X	X	Same
CF3	√	X	√	X	X	X	X	Same
DF1	X	X	X	X	X	X	X	Same
DF2	X	√	√	√	X	X	X	?
DF3	X	√	X	√	X	X	X	?

Smoking gun signals and caveats

Earth matter effects

- Hierarchy identification even for extremely small θ_{13} values
- If primary fluxes are similar, identifying Earth effects is hard
- [flux-mixing scenario] $\leftrightarrow$ [split positions] mapping still preliminary

Shock wave effects

- Presence / absence independent of collective effects
- Stochastic density fluctuations: may partly erase the shock wave imprint
- Turbulent convections behind the shock wave: gradual depolarization effects

Neutronization burst signal

- Robust, but needs Ar detector with good time resolution

Some open questions

Better analytical understanding of collective effects

- Development of “pendular oscillations”
- Prediction of positions and widths of spectral swaps
- Multi-angle decoherence effects

Effect of ν oscillations on SN astrophysics

- Shock wave dynamics
- R-process nucleosynthesis