# Signatures of supernova neutrino oscillations

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Ha$\nu$se 2011
DESY, Hamburg, July 22, 2011

# Outline

1. Neutrino flavor conversions
    - Collective flavor conversions
    - Oscillations due to the MSW effect

2. Neutrino signals at detectors
    - Spectral split and Earth matter effects
    - Shock wave effects
    - Neutronization burst
    - Indirect oscillation signals

3. Concluding remarks

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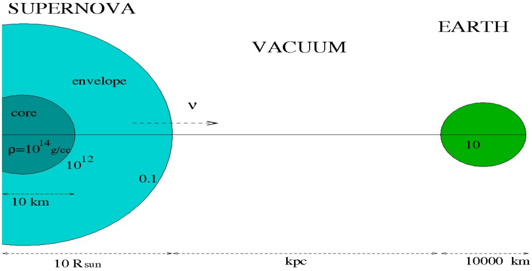
# Oscillations of SN neutrinos



**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

## Neutrino-electron forward scattering: MSW effects (1999 –)

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

## Neutrino-neutrino forward scattering: Collective effects (2006 –)

- Significant flavor conversions near the neutrinosphere : ($\rho \sim 10^{6-10}$ g/cc)
- Synchronized osc → bipolar osc → spectral split
- Single spectral split: In IH,
  $\bar{\nu}_e$ and $\bar{\nu}_\mu$ spectra swap completely
  $\nu_e$ and $\nu_\mu$ spectra swap for $E > E_c$
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# Changing paradigm of SN neutrino oscillations

## Multiple spectral splits (2008 –)

- “Single spectral split” valid only when $L_{\nu_e} \approx L_{\bar{\nu}_e} \gtrsim L_{\nu_\mu}$
- In general, both $\nu_e \leftrightarrow \nu_y$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_y$ swaps take place, in sharply separated energy regions
$$\begin{pmatrix} \nu_x \\ \nu_y \end{pmatrix} = \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix}$$
- Three flavour effects: even $\nu_e \leftrightarrow \nu_x$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_x$ swaps take place, in sharply separated energy regions
- The swapped / unswapped energy regions depend on primary fluxes and mass hierarchy

## Multi-angle effects (2008 –)

- Smoothening of flavor conversion features
- Suppression of flavor conversions
- Effect of neutrino background vis a vis normal matter

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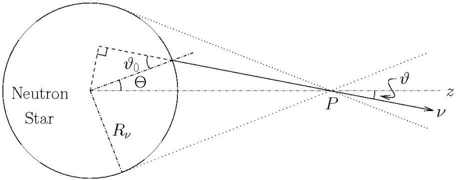
# Single-angle approximation

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

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

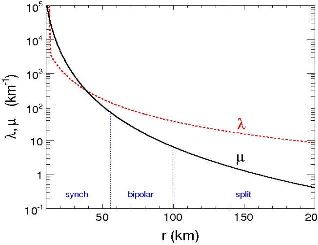


Duan, Fuller, Carlson, Qian, PRD 2006

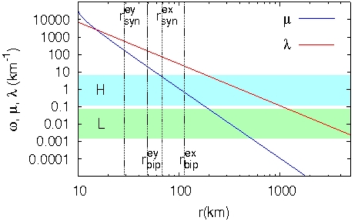
Single-angle: All neutrinos face the same average $\nu\nu$ potential [effective averaging of $(1 - \cos\theta_{pq})$]

# Sequential dominance of collective effects (Fe core)

Two-flavor



Three-flavor



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

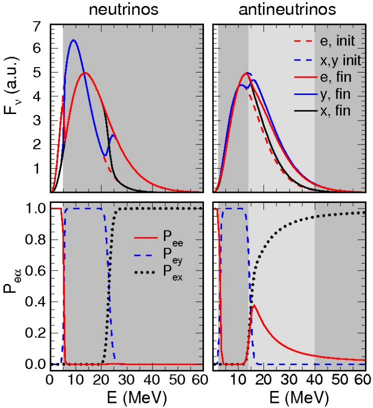
- Regions of synchronized oscillations, bipolar oscillations and spectral split are reasonably well-separated.

Fogli, Lisi, Marrone, Mirizzi, JCAP 0712, 010 (2007)

- With three flavors, factorization into two-flavor effects possible

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

# Three-flavor effects on neutrino spectra



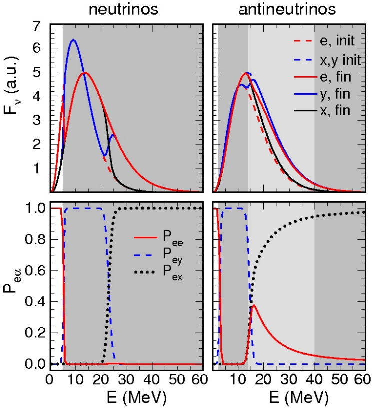
- $\nu_e \leftrightarrow \nu_y$ swap first
- Additional $\nu_e \leftrightarrow \nu_x$ swap
- Can sometimes effectively reverse earlier $\nu_e \leftrightarrow \nu_y$ split
- $\nu_e \leftrightarrow \nu_x$ swap more likely to be incomplete / non-adiabatic

A. Friedland, PRL 2010

Dasgupta, Mirizzi, Tamborra, Tomas, PRD 2010

How do primary spectra determine swapped regions ?

# Three-flavor effects on neutrino spectra



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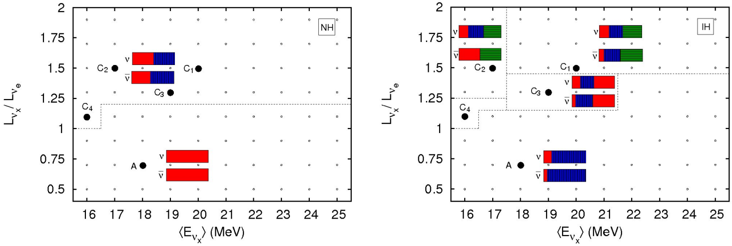
# Swap patterns with $\langle E_{\nu_\mu} \rangle$ and $L_{\nu_\mu}$



No swap, $e \leftrightarrow y$ swap, $e \leftrightarrow x$ swap

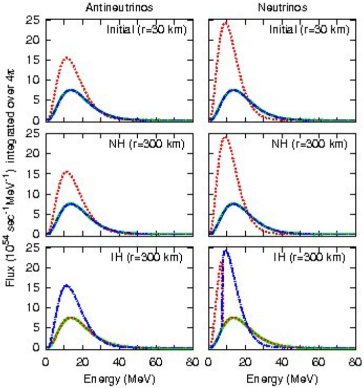
- $\langle E_{\nu_e} \rangle = 12$ MeV, $\langle E_{\bar{\nu}_e} \rangle = 15$ MeV
- $L_{\nu_e} = L_{\bar{\nu}_e}$
- For lower $\langle E_{\nu_e} \rangle$, scale $\langle E_{\nu_\mu} \rangle$ appropriately
- A: $L_{\nu_e} \gtrsim L_{\nu_\mu}$, typical of accretion phase
- C: $L_{\nu_e} \lesssim L_{\nu_\mu}$, typical of cooling phase

Single-angle results

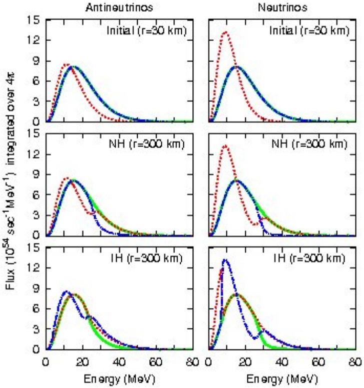
S. Choubey, B. Dasgupta, AD, A. Mirizzi, arXiv:1008.0308 [hep-ph]

# Different phases: different patterns of multiple splits

Phase A



Phase C



Flavours: $\nu_e, \bar{\nu}_e, \nu_y, \bar{\nu}_y, \nu_x, \bar{\nu}_x$

Single-angle results

# Multi-angle effects

- Multi-angle effects smear the sharp features in the spectra

Fogli, Lisi, Marrone, Mirizzi, JCAP 0712, 010 (2007)

- "Multi-angle decoherence" during collective oscillations suppressed by $\nu$–$\bar{\nu}$ asymmetry
- Single-crossed spectra with low lepton asymmetry show instability in both hierarchies

Esteban-Pretel, Pastor, Tomas, Raffelt, Sigl, PRD76, 125018 (2007)

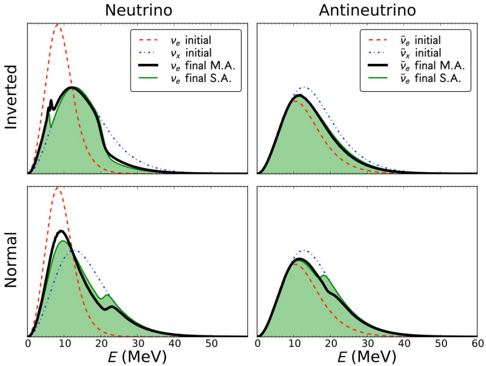
- If matter density is sufficiently high (may be possible during the accretion phase), multi-angle decoherence possible.

Esteban-Pretel, Mirizzi, Pastor, Tomas, Raffelt, Serpico, G. Sigl, PRD78, 085012 (2008)

- In accretion phase, collective oscillations are highly suppressed

Chakraborty, Fisher, Mirizzi, Saviano, Tomas, arXiv: 1104.4031, arXiv:1105.1130

# Final spectra with single- vs. multi-angle



- Collective oscillations are suppressed by the multi-angle effects of neutrinos themselves
- Additional effects of normal matter seem to be negligible
- Multi-angle effects smear the sharp features in the spectra

Duan and Friedland, PRL 2011

# Understanding onset features of Multi-angle effects

Linearized analysis for azimuthally symmetric emission:

- Neutrino background potential $\mu$ and matter background potential $\lambda$ appear through the combination $\bar{\lambda} = \lambda + \epsilon\mu$ ($\epsilon$: fractional lepton number asymmetry)
- When $\mu \gg \bar{\lambda}$ or $\bar{\lambda} \gg \mu$, consistency conditions not satisfied, so no instability can form.
- Collective oscillations start only when $\bar{\lambda} \sim \mu$

Banerjee, AD, Raffelt, arXiv:1107.2308 [hep-ph]

The jury is still out on the multi-angle effects

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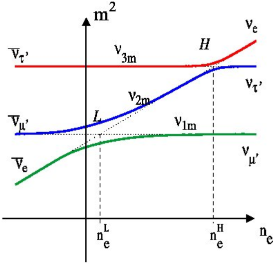
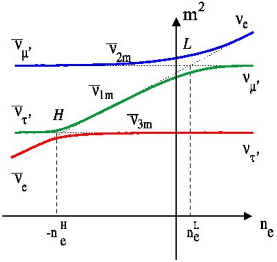
# MSW Resonances inside a SN

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 $\nu$

# 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” $\theta_{13}$ ($\sin^2\theta_{13} \lesssim 10^{-5}$) and “large” $\theta_{13}$ ($\sin^2\theta_{13} \gtrsim 10^{-3}$)
- 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 $F_{\nu_1}$ and $F_{\nu_2}$ reach the earth,

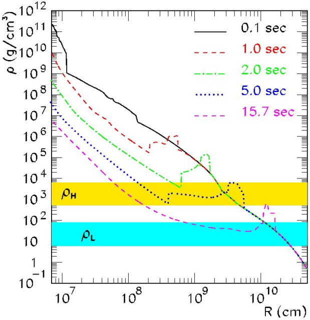
$$F^D_{\nu_e}(L) - F^D_{\nu_e}(0) \;=\; (F_{\nu_2} - F_{\nu_1}) \times \sin 2\theta^{\oplus}_{12} \sin(2\theta^{\oplus}_{12} - 2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{\oplus} L}{4E}\right)$$

(Sign changes for antineutrinos)

- $p = 0 \Rightarrow F_{\nu_1} = F_{\nu_2}\;, \quad \bar{p} = 0 \Rightarrow F_{\bar{\nu}_1} = F_{\bar{\nu}_2}$
- 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 $\bar{p}$ value
- Spectral splits $\Rightarrow$ the value of $p/\bar{p}$ may vanish in a part of the spectrum.

# Shock wave and adiabaticity breaking

When shock wave passes through a resonance region (density $\rho_H$ or $\rho_L$):

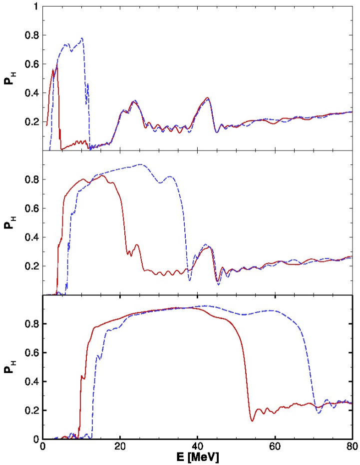


- adiabatic resonances may become momentarily non-adiabatic
- Sharp changes in the final spectra even if the primary spectra change smoothly

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

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

# Change in probability during the shock wave



- $\frac{E_{res}}{25MeV} \approx \frac{600}{Y_e\ \rho(g/cc)}$
- With time, resonant energies increase
- $p$ or $\bar{p}$ is energy-dependent and time-dependent

$t =$

2, 2.5, 3, 3.5, 4, 4.5 sec

Tomas, Kajhelriess, Raffelt, AD, Janka, Scheck, JCAP 0409, 015 (2004)

Kneller, McLaughlin, Brockman, PRD 77, 045023 (2008)

# Turbulence

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

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

- For amplitude $\lesssim 1\%$, turbulence effectively two-flavor
- For large $\theta_{13}$, shock effects likely to survive
- Jury still out

Kneller and Volpe, PRD 82, 123004 (2010)

For details, see talk by Kneller

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# The major reactions at the detectors)

## Water Cherenkov detector: (events at SK)

- $\bar{\nu}_e p \to n e^+$: ($\sim$ 7000 – 12000)
  $\Delta_{\rm WC}/{\rm MeV} = 0.47\sqrt{E_e/{\rm MeV}}$
- $\nu e^- \to \nu e^-$: $\approx$ 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)
  $\Delta_{\rm SC}/{\rm MeV} = 0.075\sqrt{E_e/{\rm MeV}}$
- $\nu + {}^{12}C \to \nu + X + \gamma$ (15.11 MeV)
- $\nu p \to \nu p$

# Liquid Ar and lead detector

**Liquid Argon detector:**

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

$$\Delta_{\mathrm{LAr}}/\mathrm{MeV} = 0.11\sqrt{E_e/\mathrm{MeV}} + 0.02\, E_e/\mathrm{MeV}$$

**Lead detector:**

- $\nu_e +{}^{208} Pb \rightarrow{}^{207} Bi + n + e^-$
- $\nu_e +{}^{208} Pb \rightarrow{}^{206} Bi + 2n + e^-$
- $\nu_x +{}^{208} Pb \rightarrow{}^{207} Pb + n$
- $\nu_x +{}^{208} Pb \rightarrow{}^{206} Pb + 2n$

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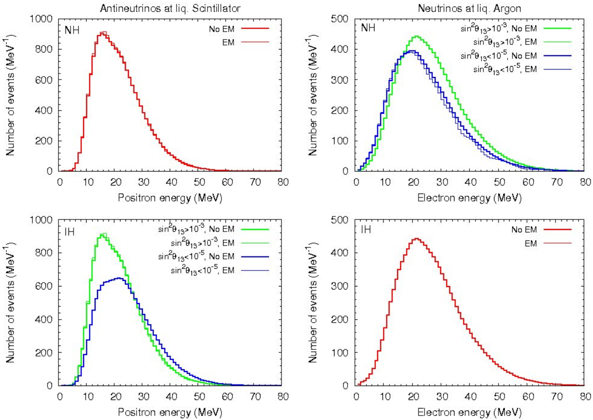
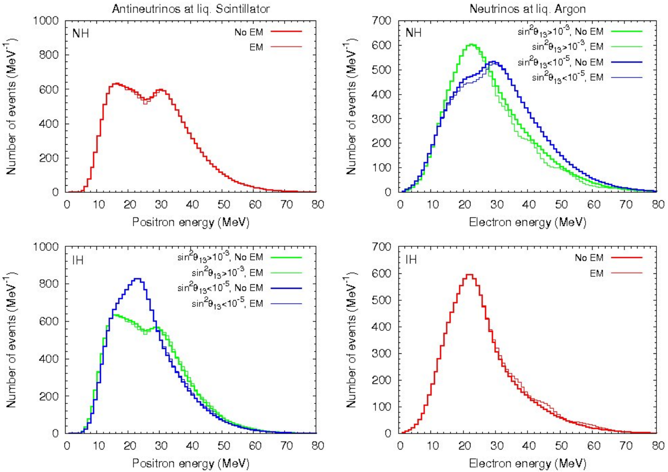
# Spectra at detectors with Earth effects: phase A



- Spectral splits not visible
- Earth effects possibly visible in neutrinos

Single-angle

# Spectra at detectors with Earth effects: phase C



- Spectral split may be visible as “shoulders”
- Earth effects possibly visible, more prominent in $\nu_e$

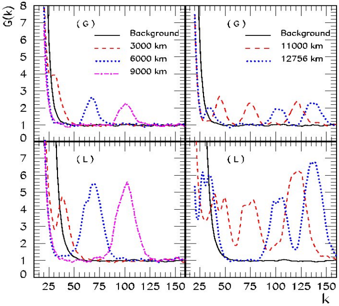
Single-angle

# 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)

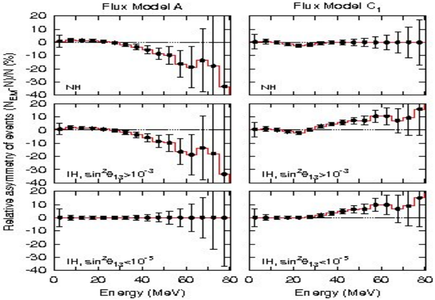
- Detection of Earth effects is practical, especially at a scintillation / liquid Argon detector.
- If Earth effect oscillations are in only a part of the spectrum, that region may be difficult to identify

# 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 400 kt water Cherenkovs



single-angle

S. Choubey et al., arXiv:1008.0308 [hep-ph]

### Robust experimental signature

- Earth effects can identify nonzero $p/\bar{p}$

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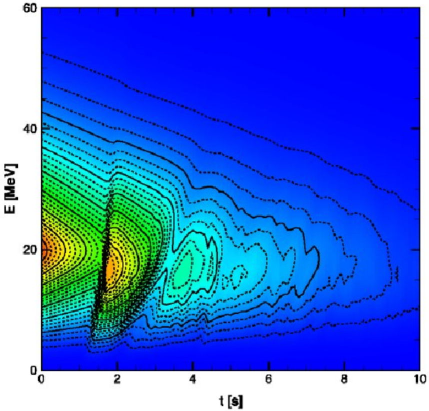
# Time dependent spectral evolution during shock wave



2D simulation

Positron spectrum
(inverse beta reaction)

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

Three-flavor calculation:
Dip in positron spectrum with IH and large $\theta_{13}$

Gava, Kneller, Volpe and McLaughlin, PRL 103, 071101 (2009)

# 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.
- When shock front is at density $\rho$, it gives dip/peak in the above quantities at $\frac{E_{res}}{25 MeV} \approx \frac{600}{Y_e \ \rho(g/cc)}$
- $\Rightarrow$ 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 effects present in $\nu_e$ only for NH $\oplus \sin^2\theta_{13} \gtrsim 10^{-5}$
- Shock effects present in $\bar{\nu}_e$ only for IH $\oplus \sin^2\theta_{13} \gtrsim 10^{-5}$
- Absence of shock effects gives no concrete signal. primary spectra too close ? turbulence ?

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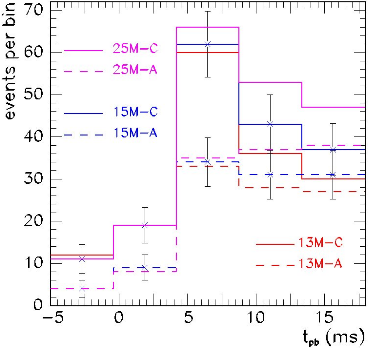
# Vanishing neutronization ($\nu_e$) burst



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

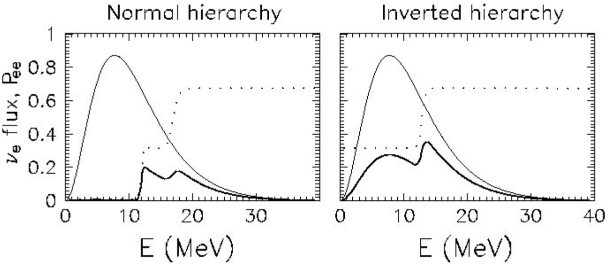
H. T. Janka, A. Marek and M. Rampp

PRD **71**, 063003 (2005)

- Time resolution of the detector crucial for separating $\nu_e$ burst from the accretion phase signal

Burst signal vanishes for NH $\oplus \sin^2\theta_{13} \gtrsim 10^{-3}$

# 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

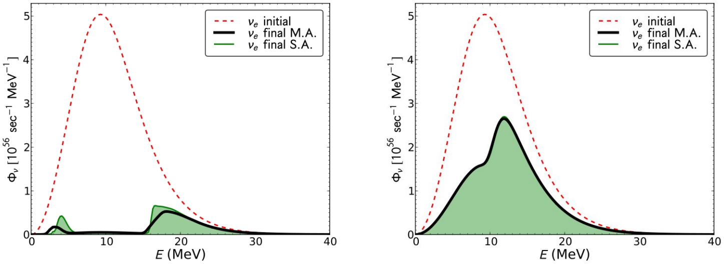
H.Duan, G.Fuller, Y.Z.Qian, PRD77, 085016 (2008)

- Positions of splits fixed by initial spectra

B.Dasgupta, AD, A. Mirizzi, G.G.Raffelt, PRD77, 1130007 (2008)

- $\nu_e$ suppression more at low energy: Ar detector crucial
- Identification of O-Ne-Mg supernova ??

# Multi-angle effects in O-Ne-Mg spectral splits



Cherry, Fuller, Carlson, Duan, Qian, PRD 82, 085025 (2010)

Results qualitatively the same even with multi-angle effects

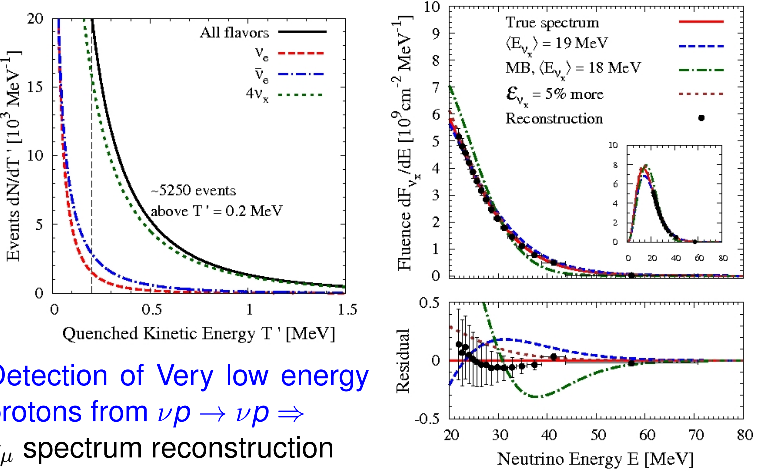
# Outline

1. Neutrino flavor conversions
   - Collective flavor conversions
   - Oscillations due to the MSW effect

2. Neutrino signals at detectors
   - Spectral split and Earth matter effects
   - Shock wave effects
   - Neutronization burst
   - Indirect oscillation signals

3. Concluding remarks

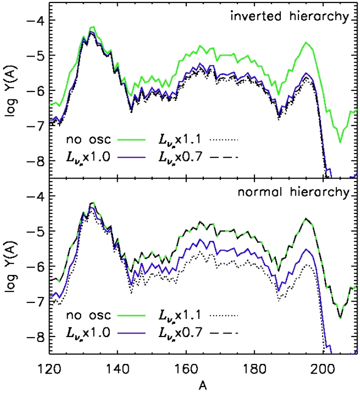
# NC events at a scintillator



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

Dasgupta and Beacom, PRD 83, 113006 (2011)

# R-process nucleosynthesis

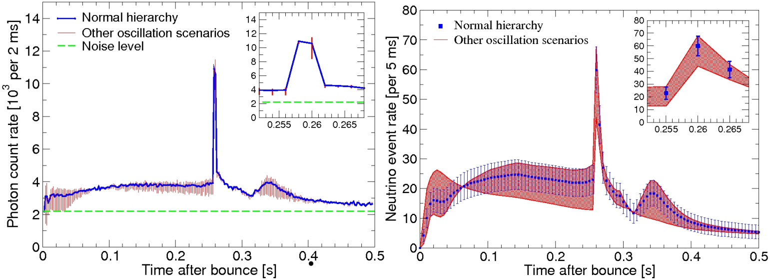


- Significant suppression effect in IH
- NH effects highly dependent on flux ratios
- Magnitude of effect dependent on astrophysical conditions

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

# QCD phase transition

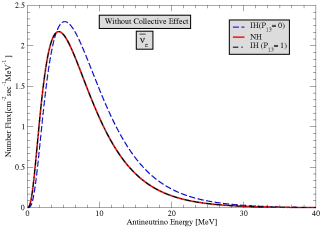
- Sudden compactification of the progenitor core during the QCD phase transition
- Prominent burst of $\bar{\nu}_e$, visible at IceCube and SK

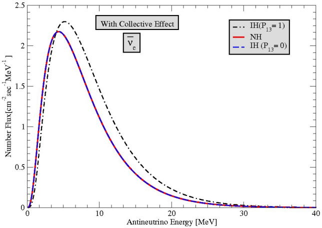


Dasgupta et al, PRD 81, 103005 (2010)

# 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)

# Outline

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# Smoking gun signals and caveats

## Earth matter effects

- Identification of nonzero $p/\bar{p}$
- If primary fluxes are similar, identifying Earth effects is hard
- Multi-angle effects still to be understood
- Better results with $\nu_e$ spectrum $\Rightarrow$ Ar detector crucial

## 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

# Inverse SN neutrino problem

Observe

- $\nu_e/\bar{\nu}_e$ spectra
- NC events
- time variation of the signal
- Earth matter effects

Determine

- Primary fluxes
- Shock propagation

Not impossible, but many gaps still to be filled

# If $\theta_{13}$ is large

- Shock wave effects likely to be prominent
  Hierarchy determination may be easier
  Shock tracking may be possible
- $P_H = 0 \Rightarrow$ can reconstruct spectra just after collective effects
- Earth effects may tell if $p$ or $\bar{p}$ is nonzero. This can help reconstruct spectra before collective effects
- Experimental measurement of collective effects ??

# Theory-independent measurements

Still too many uncertainties in fluxes, $p$ and $\bar{p}$ ?

One can nevertheless make the following measurements / analyses:

- $\nu_e$ and $\bar{\nu}_e$ spectra
- NC spectra through scintillation detectors
- single- and double-neutron events at Pb detectors
- Time modulation of flux, average energy, higher moments
- Time dependent, relative luminosities at two detectors
- Oscillatory spectral modulations for Earth effects
- Other non-thermal features in the spectrum