Neutrinos and supernova astrophysics

Amol Dighe

Tata Institute of Fundamental Research
Mumbai, India

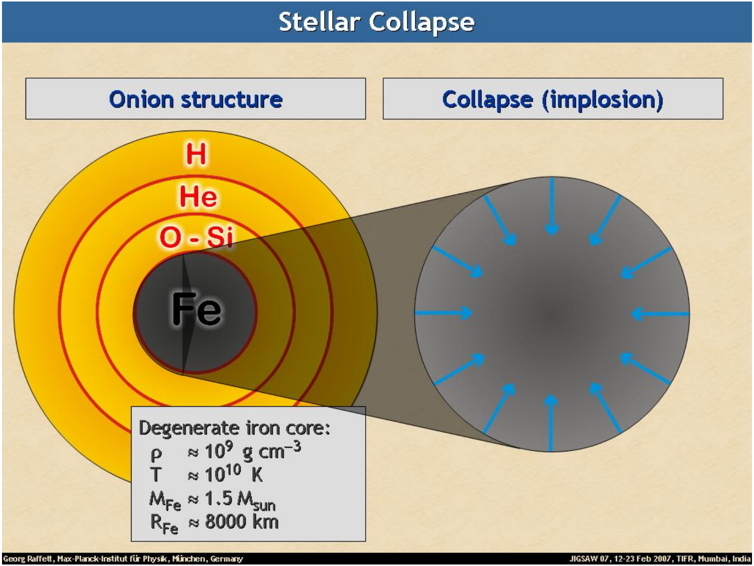
NC-HEPC 2013, Guwahati, Feb 13, 2013

Neutrinos and SN astrophysics

1. Supernova explosion and neutrino fluxes
2. Effects of collective flavor conversions
3. Effects of MSW flavor conversions
4. What we learnt from SN1987A
5. Expectations from future observations

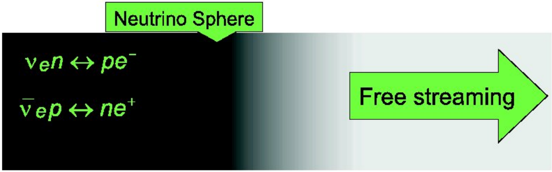
Neutrinos and SN astrophysics

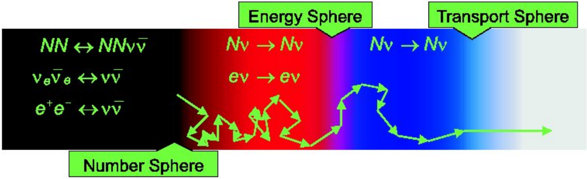
The would-be supernova before the collapse



Trapped neutrinos before the collapse

- Neutrinos trapped inside “neutrinospheres” around $\rho \sim 10^{10}$g/cc.

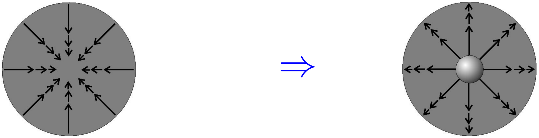




- Escaping neutrinos: $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$

Core collapse, shock wave, neutrino emission: 10 sec

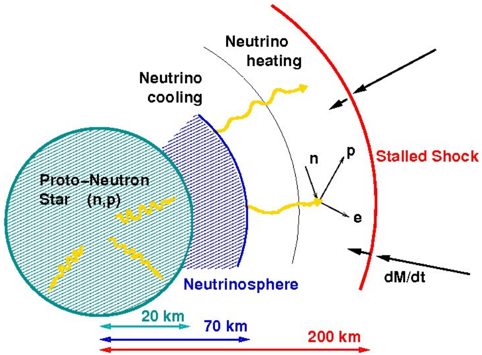
Gravitational core collapse $\Rightarrow$ Shock Wave



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

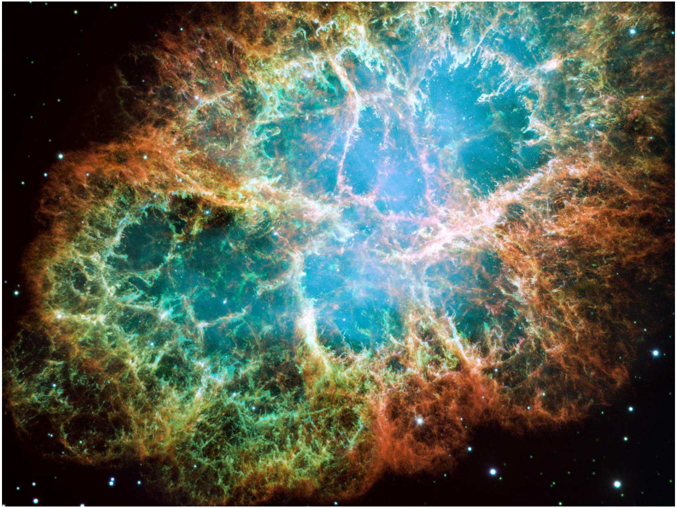
- Neutronization burst: ν_e emitted for $\sim$ 10 ms
- Accretion phase: Larger $\nu_e/\bar{\nu}_e$ luminosity
- Cooling through neutrino emission:
  all $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ with similar luminosities
- Energy $\sim 10^{53}$ erg emitted within $\sim$ 10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

The explosion: the next $\sim$ 10 hours



- Neutrino heating needed for pushing the shock wave
- Large scale convection also needed
- Resulting hydrodynamic "SASI" instabilities cause explosions (according to simulations)

The star, a millennium after explosion

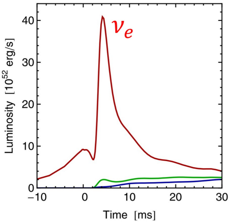


(Crab nebula, supernova seen in 1054)

Neutrino fluxes: luminosities

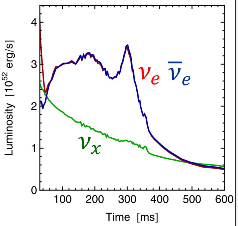
Three Phases of Neutrino Emission

Prompt ν_e burst



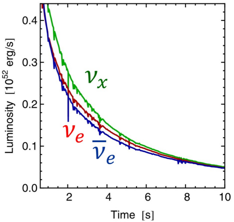
- Shock breakout
- De-leptonization of outer core layers

Accretion



- Shock stalls $\sim$ 150 km
- Neutrinos powered by infalling matter

Cooling

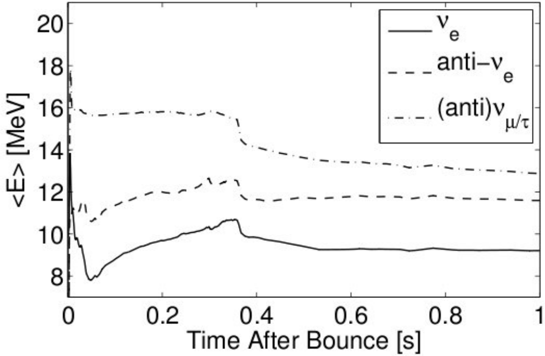


Cooling on neutrino diffusion time scale

- 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

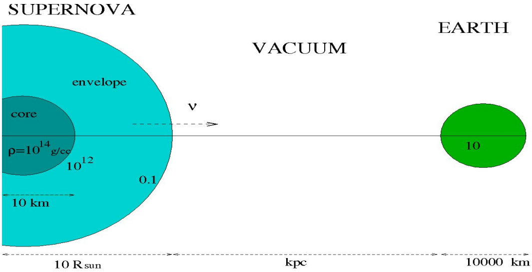


$10.8 M_\odot$ star

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 $\to$ bipolar osc $\to$ spectral split
- Sensitivity to much smaller $\sin^2\theta_{13}$ than MSW effects

Now that θ_{13} is known to be large,
strong sensitivity to mass hierarchy due to both effects

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

Now that θ_{13} is known to be large,
strong sensitivity to mass hierarchy due to both effects

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

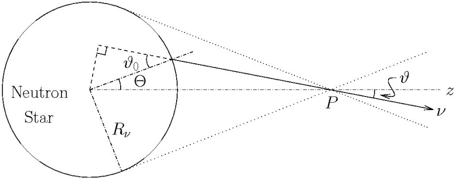
Now that θ_{13} is known to be large,
strong sensitivity to mass hierarchy due to both effects

Neutrinos and SN astrophysics

Non-linearity from neutrino-neutrino interactions

- 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

- Equation of motion:

$$\frac{d\rho}{dt} = i\,[H(\rho), \rho]$$

Note: ρ is a 3×3 matrix

"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)

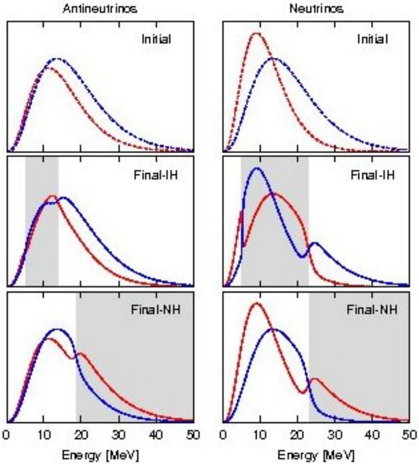
Spectral split/swap:

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)

Multiple spectral splits



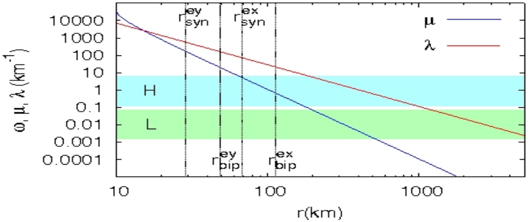
- Spectral splits as boundaries of swap regions
- Splits possible both for ν_e and $\bar{\nu}_e$
- Split positions depend on NH/IH

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

Problems and open questions in collective effects

- New non-linear effects: how to understand/model in terms of other known phenomena ?
- Many answers known only with the single-angle approximation (all neutrinos at a point face the same average $\nu\nu$ potential [effective averaging of $(1 - \cos\theta_{pq})$]). How good is this 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 ?
- Work in progress....

Different phenomena occuring sequentially



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

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

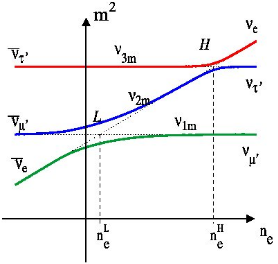
Fogli, Lisi, Marrone, Mirizzi, JCAP 0712, 010 (2007), B.Dasgupta and AD, PRD77, 113002 (2008)

- 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.

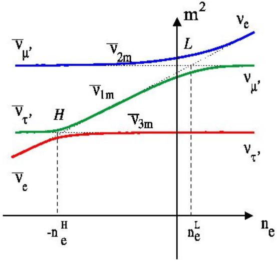
Neutrinos and SN astrophysics

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
- Now that θ_{13} is known to be large, adiabatic except during the passage of the shock wave

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
  (except during the passage of the shock wave)
- 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

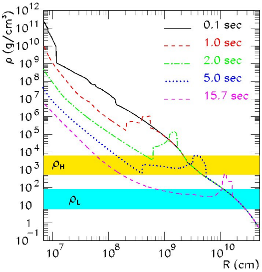
- If F_{ν_1} and F_{ν_2} reach the earth,

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

(Sign changes for antineutrinos)

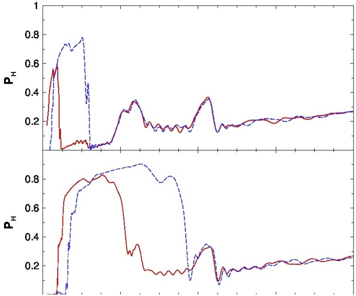
- $p = 0 \Rightarrow F_{\nu_1} = F_{\nu_2}$, $\quad \bar{p} = 0 \Rightarrow F_{\bar{\nu}_1} = F_{\bar{\nu}_2}$
- Nonzero Earth matter effects require
  - Neutrinos: $p \neq 0$
  - Antineutrinos: $\bar{p} \neq 0$
- Possible to detect Earth effects since they involve oscillatory modulation of the spectra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

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 $\Rightarrow$ 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)

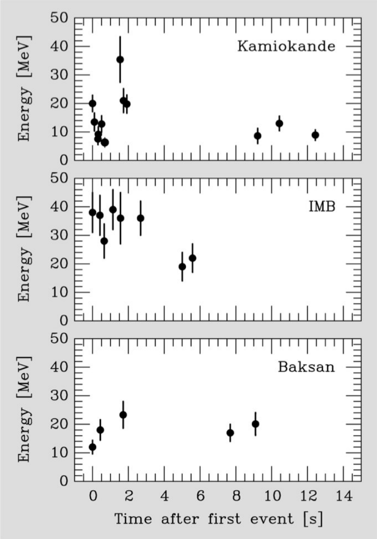
- For "small" amplitude, turbulence effectively two-flavor
- For large θ_{13}, shock effects likely to survive
- Jury still out

Kneller and Volpe, PRD 82, 123004 (2010)

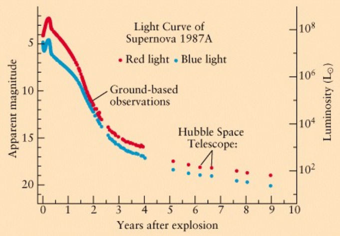
Neutrinos and SN astrophysics

SN1987A: neutrinos and light

Neutrinos: Feb 23, 1987

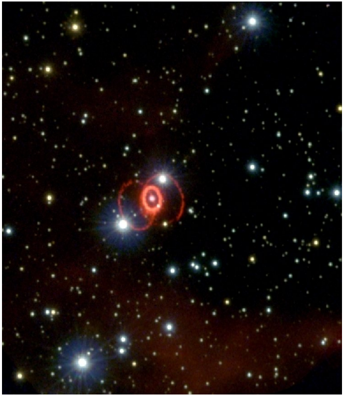


Light curve: 1987-1997



SN1987A: what did we learn ?

Hubble image: now



- 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
- Strong constraints on new physics models obtained (neutrino decay, Majorans, axions, extra dimensions, ...)

Neutrinos and SN astrophysics

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

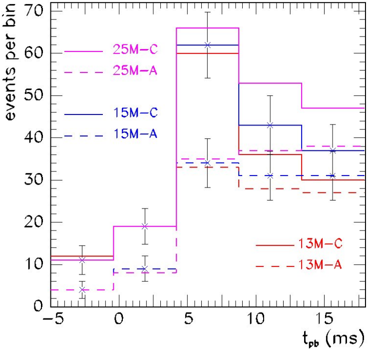
Carbon-based scintillation detector: $\sim$ 300 events/kt

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

Liquid Argon detector: $\sim$ 300 events /kt

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

Vanishing neutronization (ν_e) burst



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

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

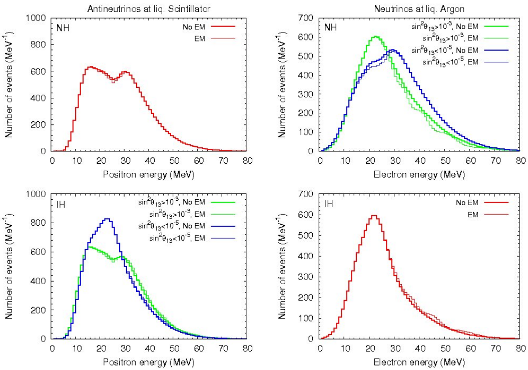
H. T. Janka, A. Marek and M. Rampp

PRD **71**, 063003 (2005)

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

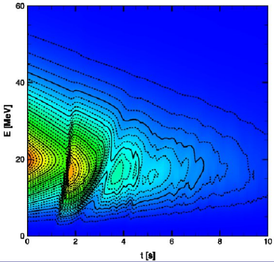
- Burst in CC suppressed by $\sim \sin^2\theta_{13} \approx 0.025$ for NH, only by $\sim \sin^2\theta_{12} \approx 0.3$ for IH
- Time resolution of the detector crucial for separating ν_e burst from the accretion phase signal

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

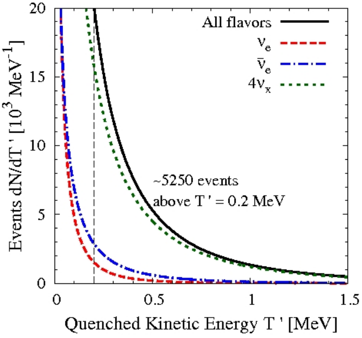
Time-dependent dip/peak features in $N_{\nu_e,\bar{\nu}_e}(E)$, $\langle E_{\nu_e,\bar{\nu}_e} \rangle$, ...

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

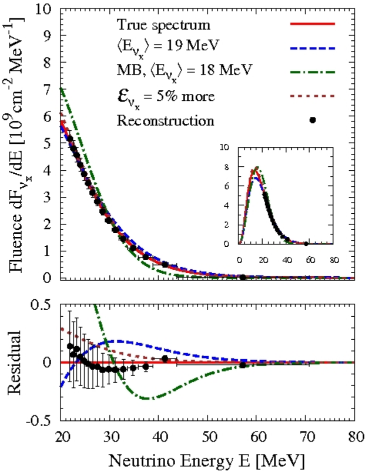
Identifying mixing scenario: independent of collective effects

- 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 ?

NC events at a scintillator

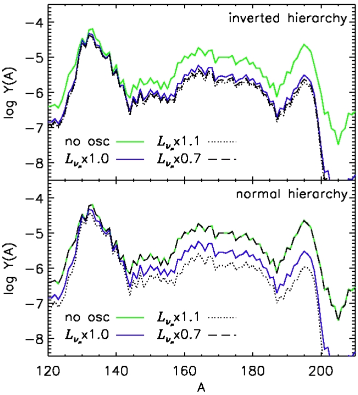


Detection of Very low energy protons from $\nu p \to \nu p \Rightarrow$ ν_μ spectrum reconstruction



Dasgupta and Beacom, PRD 83, 113006 (2011)

R-process nucleosynthesis

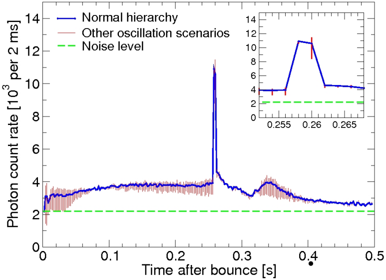


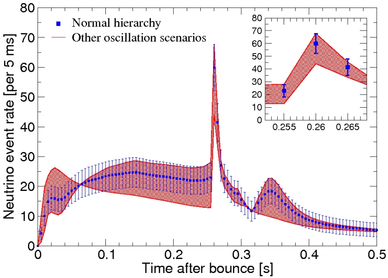
- Significant suppression effect in IH
- NH effects highly dependent on flux ratios
- Magnitude of effect dependent on astrophysical conditions

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

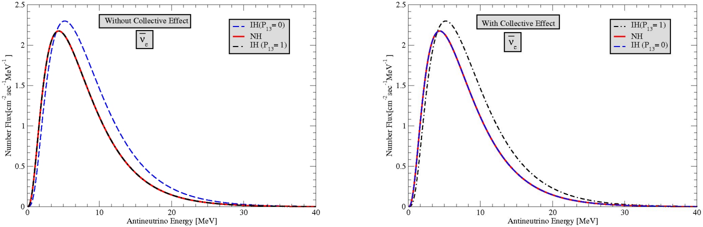




Dasgupta et al, PRD 81, 103005 (2010)

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)

SN neutrinos for particle physics and astrophysics

With large θ_{13}, mass hierarchy easier to identify!

- 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.

SN astrophysics through neutrinos

- Primary fluxes, density profiles, shock wave propagation, QCD phase transition, nucleosynthesis... a plethora of astrophysical information in the neutrino signal
- For extracting this information from the neutrino signal, a better understanding of collective effects is essential !
- A lot more work needed before we solve the “inverse SN neutrino problem”.

SN neutrinos for particle physics and astrophysics

With large θ_{13}, mass hierarchy easier to identify!

- 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.

SN astrophysics through neutrinos

- Primary fluxes, density profiles, shock wave propagation, QCD phase transition, nucleosynthesis... a plethora of astrophysical information in the neutrino signal
- For extracting this information from the neutrino signal, a better understanding of collective effects is essential !
- A lot more work needed before we solve the "inverse SN neutrino problem".