Supernova neutrino oscillations

Probing neutrino-neutrino interactions in dense media

Amol Dighe

Tata Institute of Fundamental Research
Mumbai, India

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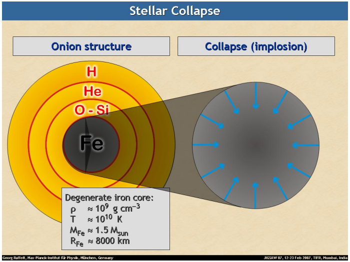
Supernova neutrinos

Neutrinos and SN astrophysics

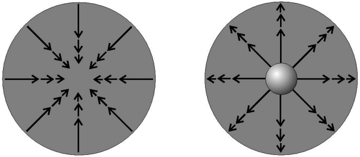
1. Supernova explosion and neutrino fluxes
2. Collective flavor conversions
3. MSW flavor conversions
4. Supernova neutrino observables

A collaboration of all fundamental forces

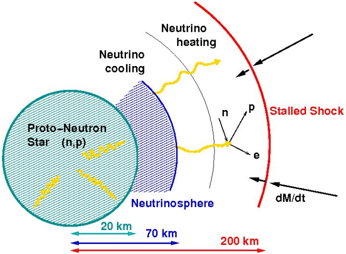
Gravity ⇒



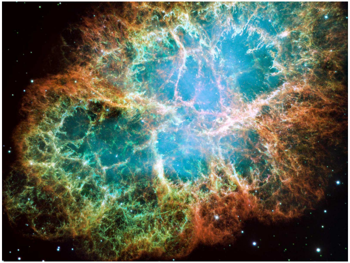
Nuclear forces ⇒



Neutrino push ⇒



Hydrodynamics ⇒

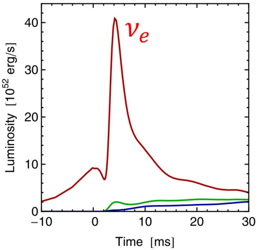


(Crab nebula, SN seen in 1054)

Neutrino fluxes in three phases

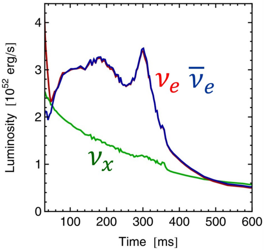
Three Phases of Neutrino Emission

Prompt ν_e burst



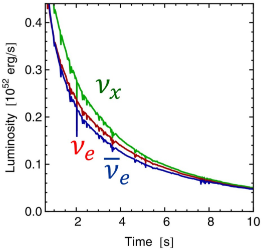
- Shock breakout
- De-leptonization of outer core layers

Accretion



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

Cooling

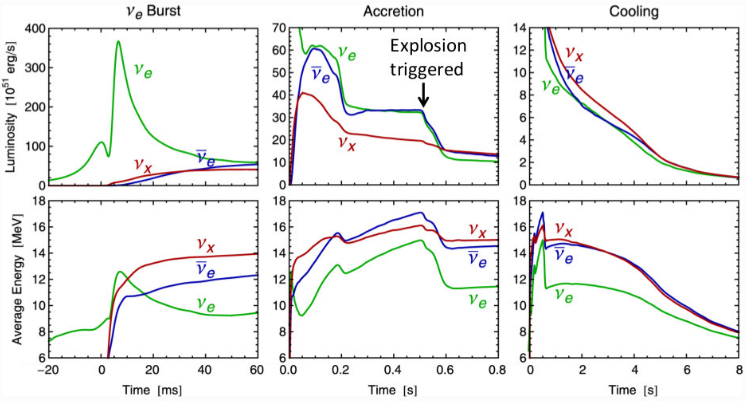


Cooling on neutrino diffusion time scale

- 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]

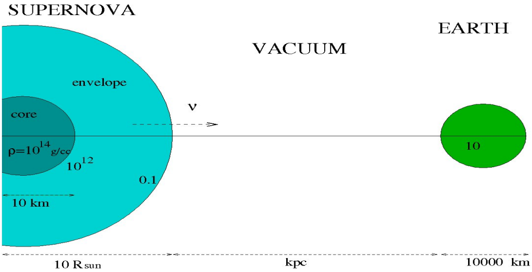
Luminosities and energy spectra



Garching group

- 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 mass hierarchy (MH), as long as $\sin^2\theta_{13} \gtrsim 10^{-5}$

Collective effects on neutrino conversions (post-2006)

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

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

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Changing paradigm of supernova neutrino oscillations

Multi-angle collective effects (post-2010)

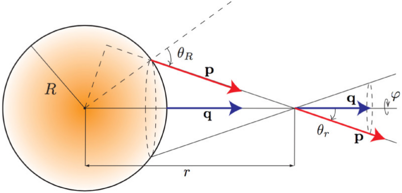
- Suppression of oscillations by high matter density
- Linear stability analysis: Onset of oscillations analytically interpreted as an exponentially growing instability
- Asymmetries and fluctuations leading to instabilities
- Will flavour instabilities affect explosions ?

Neutrinos and SN astrophysics

Non-linearity from neutrino-neutrino interactions

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

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



Duan, Fuller, Carlson, Qian, PRD 2006

- Equation of motion:

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

- Dimension of ρ matrix: $(3 \times N_{E-bins} \times N_{\theta-bins})$

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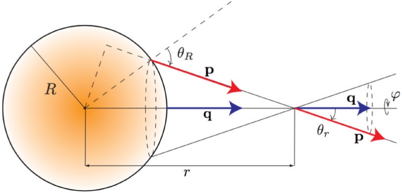

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"Collective" effects: qualitatively new phenomena

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

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

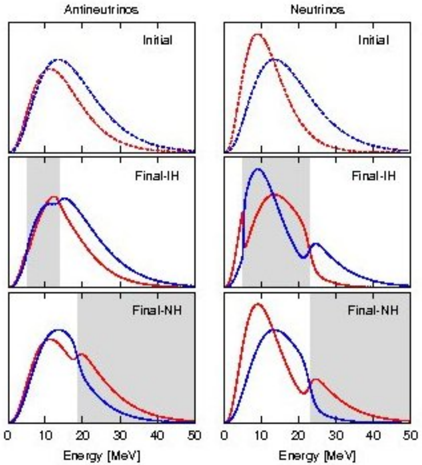
Spectral split/swap:

ν_e and ν_x ($\bar{\nu}_e$ and $\bar{\nu}_x$) spectra swap 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

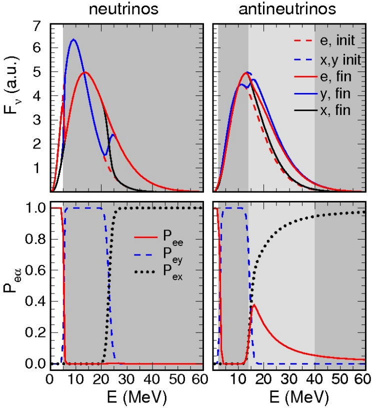


- Spectral splits as boundaries of swap regions
- Splits possible both for ν_e and $\bar{\nu}_e$
- Split positions depend on NH/IH

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

Three-flavor collective effects

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



- $\nu_e \leftrightarrow \nu_y$ 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

Things are not that straightforward....

- Most analyses with single-angle approximation:
(All neutrinos at a point face the same average $\nu\nu$ potential) $\Rightarrow$ [Effective averaging of $(1 - \cos\theta_{pq})$].

Multi-angle effects

- At extremely high matter densities instabilities are completely suppressed

Chakraborty et al., arXiv:1105.1130

- Collective oscillations are suppressed by the multi-angle effects of neutrinos themselves at large densities

Duan et al., PRL 2011

- But the final spectra may still be similar to single-angle, with smoothening of sharp features

Fogli et al., JCAP 2007, Duan et al., PRL 2011

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Linear stability analysis: do instabilities grow ?

- Azimuthally symmetric emission, large distance from neutrinosphere, small amplitude expansion $\Rightarrow$ Linearized equations of motion

$$
\begin{aligned}
i\partial_r S_{\omega,u} &= [\omega + u(\lambda + \epsilon\mu)]\, S_{\omega,u} \\
&- \mu \int du'\, d\omega'\, (u+u')\, g_{\omega' u'}\, S_{\omega',u'}\,,
\end{aligned}
$$

Banerjee, AD, Raffelt

$$
\begin{aligned}
\omega &\equiv \Delta m^2/(2E) \\
u &\equiv \sin^2\vartheta \\
\epsilon &\equiv \int du\, d\omega\, g_{\omega,u}\,, \\
\lambda &\equiv \frac{\sqrt{2}\, G_{\mathrm{F}}\, [n_e(r) - n_{\bar{e}}(r)]}{2r^2}\,, \\
\mu &\equiv \frac{\sqrt{2}\, G_{\mathrm{F}} \Phi_{\bar{\nu}_e}(R) R^2}{8\pi r^4}\,.
\end{aligned}
$$

Complex solutions and instabilities

- Look for solutions of the form

$$S_{\omega,u} = Q_{\omega,u}\, e^{-i\Omega r} \ .$$

- A complex solution $\Omega \equiv \gamma + i\kappa$, with $\kappa > 0$, would indicate an exponentially increasing $S_{\omega,u}$.
- In terms of $Q_{\omega,u}$, the EoM becomes

$$(\omega + u\bar{\lambda} - \Omega) Q_{\omega,u} \quad = \quad \mu \int du'\, d\omega'\, (u + u')\, g_{\omega' u'}\, Q_{\omega',u'} \ .$$

This is the eigenvalue equation, to be solved for Ω to check if it is complex

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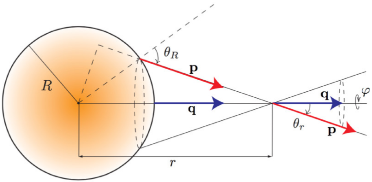
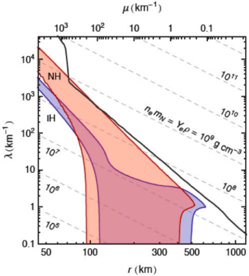
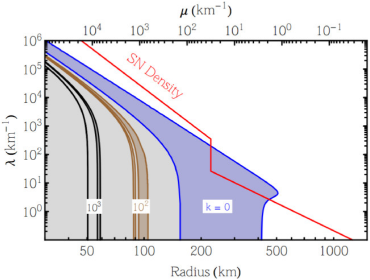
Instability footprints



Angular symmetry breaking

Spatial fluctuations





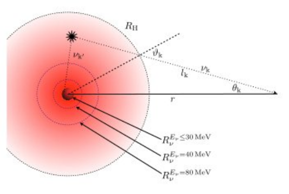
Raffelt, Sarikas, Seixas,

Chakraborty, Hansen, Izzaguirre, Raffelt

Some other developments

Halo effect

Neutrinos that undergo scattering outside the neutrinosphere can have an effect on oscillations



Fast oscillations

- Different angular distributions for different flavours $\Rightarrow$ Instabilities grow as $\mu \equiv \dfrac{\sqrt{2}\, G_{\mathrm{F}} \Phi_{\bar{\nu}_e}(R) R^2}{8\pi r^4}$ as opposed to $\omega \equiv \Delta m^2/(2E)$

  Sawyer, PRD 2005, PRL 2016, Chakraborty, Hansen, Izzaguirre, Raffelt

- Oscillations are effective deeper inside the star $\Rightarrow$ Explosion may be affected !

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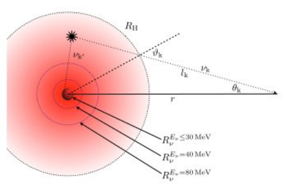

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Current understanding of collective oscillations

Work in progress...

- Multi-angle effects, matter effects, halo effects, ...
- Development of instabilities, fast oscillations, ...
- Will spectra have distinct features ?
- Will explosion be affected ?

Till situation is resolved: explore MSW effects

- The post-collective fluxes may be taken as “primary” ones on which the MSW analysis may be applied.
- Neutronization burst: only ν_e, so no collective effects
- Shock-effect and earth-effect analyses remain unchanged.

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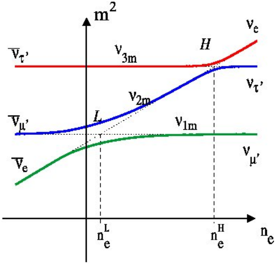
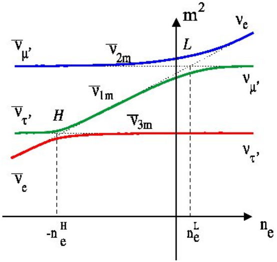
MSW Resonances inside a SN

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
- 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 $\bar{p}$

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

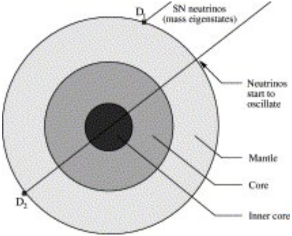
- Approximately constant with energy
  (except during the passage of the shock wave)

- 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,



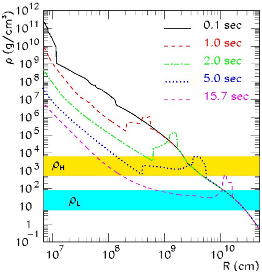
$$F^D_{\nu_e}(L) - F^D_{\nu_e}(0) = (F_{\nu_2} - F_{\nu_1}) \times$$

$$\sin 2\theta^{\oplus}_{12} \sin(2\theta^{\oplus}_{12} - 2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{\oplus} L}{4E}\right)$$

(Sign changes for antineutrinos)

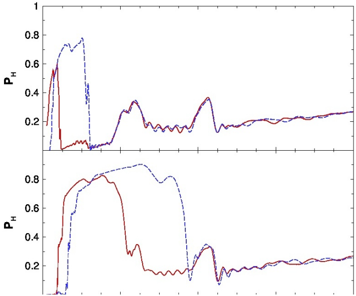
- $p = 0 \Rightarrow F_{\nu_1} = F_{\nu_2}$, $\bar{p} = 0 \Rightarrow F_{\bar{\nu}_1} = F_{\bar{\nu}_2}$
- Nonzero Earth matter effects require
  - Neutrinos: $p \neq 0$
  - Antineutrinos: $\bar{p} \neq 0$
- Possible to detect Earth effects since they involve oscillatory modulation of the spectra
- An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

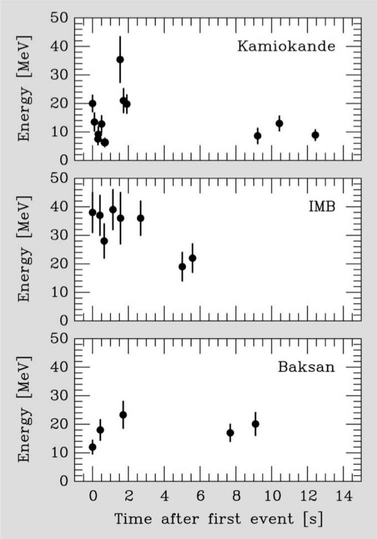
- For "small" amplitude, turbulence effectively two-flavor
- For large θ_{13}, shock effects likely to survive
- Jury still out

Kneller and Volpe, PRD 82, 123004 (2010)

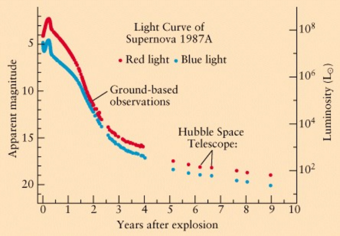
Neutrinos and SN astrophysics

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, Lorentz violation...)

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

Water Cherenkov detector:

- $\bar{\nu}_e p \to n e^+$ ($\sim$ 300 events per kt)
- $\nu e^- \to \nu e^-$ ($\sim$ 5 events per kt)
- $\nu_e +^{16} O \to X + e^-$ ($\sim 3 - 15$ events per kt)

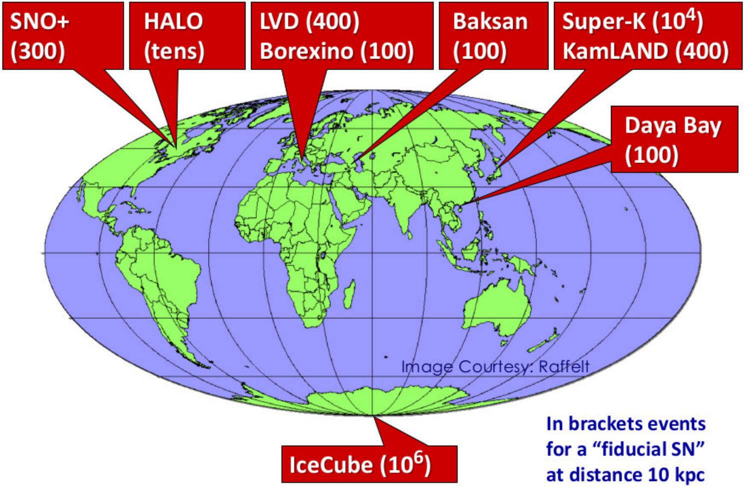
Carbon-based scintillation detector:

- $\bar{\nu}_e p \to n e^+$ ($\sim$ 300 events 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 events per kt)

SN detectors around the globe

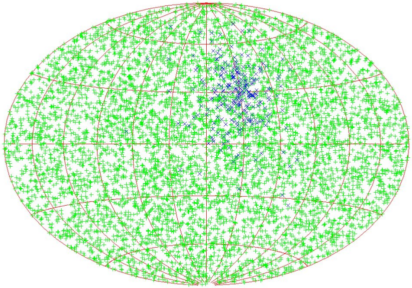


In brackets events for a "fiducial SN" at distance 10 kpc

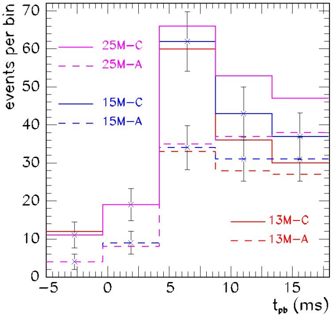
Pointing to the SN in advance

- Neutrinos reach 6-24 hours before the light from SN explosion (SNEWS network)
- $\bar{\nu}_e p \to n e^+$: nearly isotropic background
- $\nu e^- \to \nu e^-$: forward-peaked "signal"
- Background-to-signal ratio: $N_B/N_S \approx 30$–50
- SN at 10 kpc may be detected within a cone of $\sim 5^\circ$ at SK
- Adding Gd may make the pointing much better...

Beacom, Vogel 1999, Tomas et al 2003



Suppressed neutronization (ν_e) burst



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

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

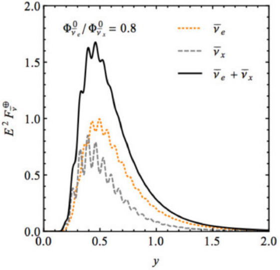
  H. T. Janka, A. Marek and M. Rampp

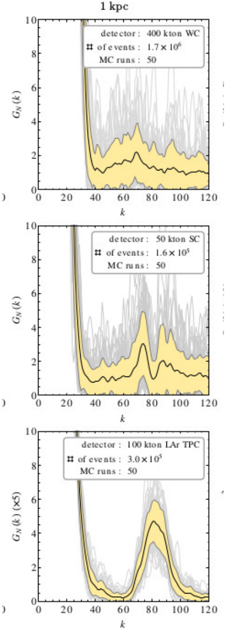
  PRD **71**, 063003 (2005)

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
- Need liquid-Ar detector (DUNE !)
- Time resolution of the detector crucial for separating ν_e burst from the accretion phase signal

Earth effects through spectral modulations

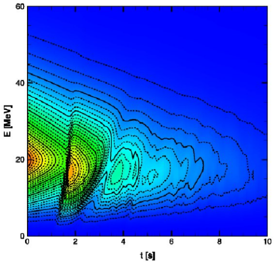




- Peak expected in Fourier transforms...
- Ratio of luminosities at two large detectors
- Not so encouraging results.

Boriello, Chakraborty, Mirizzi, Serpico, Tamborra

Shock wave effects



2D simulation
Positron spectrum
(inverse beta reaction
$\bar{\nu}_e p \to e^+ n$)

Kneller et al., PRD77, 045023 (2008)

Observable shock signals

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

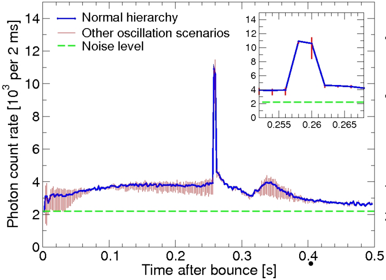
R.Tomas et al., JCAP **0409**, 015 (2004), Gava, et al., PRL 103, 071101 (2009)

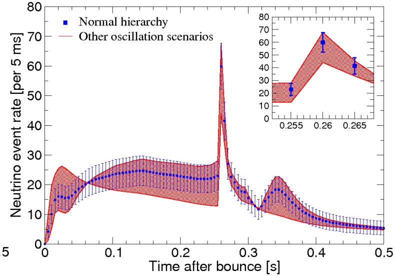
Identifying mixing scenario: independent of collective effects

- 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 ?

QCD phase transition

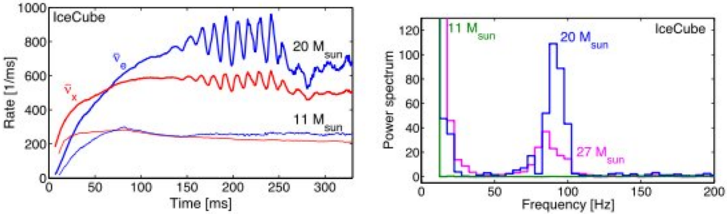
- Sudden compactification of the progenitor core during the QCD phase transition
- Prominent burst of $\bar{\nu}_e$, visible at IceCube and SK / HK





Dasgupta et al, PRD 81, 103005 (2010)

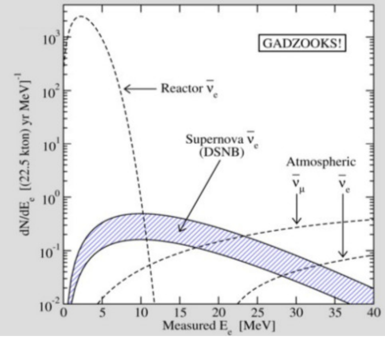
Detection of SASI instabilities



- Standing Accretion Shock Instability: global dipolar and quadrupolar deformations at the shock front
- Imprints even on top of the turbulent motion of matter
- Observable in Icecube event rate, as a high-frequency signal

Tamborra et al, PRL 2013

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)

Concluding remarks

SN neutrinos for particle physics

- With large θ_{13}, mass hierarchy easier to identify!
- Neutronization burst suppression
- Shock wave effects / earth matter effects
- Collective effects and flavour conversion instabilities

SN astrophysics through neutrinos

- Primary fluxes, density profiles, shock wave propagation, QCD phase transition, nucleosynthesis, explosion mechanism... 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 !

All new experiments should be ready for a SN burst !

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