Supernova Neutrinos

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Acknowledgments

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- Several figures borrowed from G. Raffelt
Outlines

- Core-collapse supernova explosions
  - What are they?
  - What might we learn? (i.e., why plan experiments?)
    - Astrophysics of the explosion; nucleosynthesis; neutrino properties ($\theta_{13}$, hierarchy); physics BSM
- A bit more on MSW and the explosion (existing work)
  - Signature of shock passage through resonance
  - Turbulence and neutrino signal: testing the key paradigm
    - Motivation, status of simulations
    - Neutrino evolution in Kolmogorov turbulence
- Implications
What are they?

- **Observational classification**
  - Type I: no H
    - Type Ia: Si
    - Type Ib: He, no Si
    - Type Ic: no He, no Si ...
  - Type II: H

Massive stars undergoing core collapse
**Progenitor**

- Massive ($M > 8M_\odot$) star burns H, He, C, Ne, O and Si, makes Fe core

<table>
<thead>
<tr>
<th>Table 1 Evolution of a 15-solar-mass star.</th>
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<tbody>
<tr>
<td><strong>Stage</strong></td>
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<tr>
<td>Hydrogen</td>
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<tr>
<td>Helium</td>
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<tr>
<td>Carbon</td>
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<td>Neon</td>
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<td>Oxygen</td>
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<tr>
<td>Silicon</td>
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<tr>
<td>Iron core</td>
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* The pre-supernova star is defined by the time at which the contraction speed anywhere in the iron core reaches 1,000 km s^{-1}.

- Compared to Sun which burns $10^{-1} M_\odot$ in $10^{10}$ yrs, surface luminosity is $10^4$ times larger \(\rightarrow\) will burn though a few $M_\odot$ in **only** $10^7$ yrs
- \(\rightarrow\) Occur in stellar-forming regions; diffuse \(\nu\)'s tracks rate of stellar formation
Iron core collapse

- Onion-like shell structure, with dense iron core
  - $\rho \sim 0.8 \times 10^{10} \text{ g/cm}^{-3}$, $T \sim 0.9 \times 10^{10} \text{ K}$, $R \sim 0.9 \times 10^{4} \text{ km}$
  - Electron capture at $\rho > 10^{10} \text{ g/cm}^{-3}$
  - Photodisintegration of iron
- Loss of pressure support, $\sim 1.4 M_{\odot}$ in near free-fall collapse at $v \sim c/4$ to $r \sim 30 \text{ km}$
- At $\rho \sim 4-5 \times 10^{14} \text{ g/cm}^{3}$, bounce of the inner core due to nuclear force, shock formed
- Shock travels through the outer core, looses energy to disintegration of Fe, neutrino emission, stalls in only a few milliseconds
- Material keeps falling in at rate of a few $\times 10^{-1} M_{\odot}$; if continues even for a second $\rightarrow$ black hole
Core collapse supernovae

- We know that somehow shock restarts, blows through the star
  - See explosions
  - See neutron stars
  - Detected neutrinos
  - Many of the elements of nature, including those that form our planet and bodies, made in SN and successfully blown off

For review, see, e.g., Woosley & Janka, Nature Physics 1, 147-154 (2005)
Mechanism?

- **Very rich physics:**
  - Energy transport and deposition by neutrinos
  - Convection (fluid instabilities)
  - Magnetic fields
  - Rotation
  - Nuclear equation of state
  - New particle physics?
  - etc ...
- **No clear single dominant process** -> 40 years of active research

For review, see, e.g., Woosley & Janka, Nature Physics 1, 147-154 (2005)
Present paradigm

from G. Raffelt, in turn from Janka (1993)
Basic energetics

- Gravitational binding energy, $G_N M^2/r \sim 3 \times 10^{53}$ ergs, is 10% of the rest mass.
- This energy is released in neutrinos and antineutrinos of all three active flavors.
- Visible explosion only $1-2 \times 10^{51}$ ergs, $\lesssim 1\%$ of total energy, $\sim 0.01\%$ in photons.
  - (still outshines host galaxy)

- $\rightarrow$ SN is basically a gravity powered neutrino explosion.
- Instantaneously as bright as the rest of the luminous Universe.
- Measuring the total energy in neutrinos is crucial!
What can we learn?

- **Constraints on new physics beyond the SM?**
  - Measure the total energy in neutrinos, see if any missing
- **Example:**
  - Bound on axions

From G. Raffelt
Physics BSM, continued

- Another example: constraining models of extra dimensions (ADD)
  - KK gravitons emitted by $NN \rightarrow NN\phi$
  - Cooling arguments (SN1987a):
    - $\Lambda > 30$ TeV ($n_{\text{extra dim}}=2$)
    - $\Lambda > 3$ TeV ($n_{\text{extra dim}}=3$)
    - Cullen, Perelstein, hep-ph/9904422
  - (Even stronger bounds from neutron star cooling,
    $\Lambda > 1600$ TeV ($n_{\text{extra dim}}=2$))
    - Hannestad, Raffelt, hep-ph/0103201
Robust explosions with new physics?

- New particles with right properties could carry energy from the proto-neutron star to the stalled shock
  - Supernova explosions by axion-like particles
- May even deposit too much energy ;-)
  - ->limits on decaying neutrinos
SN1987a vs future galactic SN

- Bounds currently come from $O(20)$ events from SN1987a. Too few events + uncertainties in the SN models ...
  - important not to overinterpret!
  - Smirnov, Spergel, Bahcall, PRD 49, 1389 (1994) “Is large lepton mixing excluded?” almost ruled out LMA

- Good data from the next SN needed!
  - Super-K 8000 (anti-$\nu_e$ p), 300 ($\nu_x^{16}O$), 200 ($\nu_x e^-$)...
  - KamLAND 300, LVD 200, Mini-BOONE 200, Borexino 100...
  - Hanohano $\sim$ 3000 (10 times KamLAND) - comparable to SK

- Estimates for our Galaxy range from 1 to 5 explosions per century
  - Counting progenitors, (1-3)/100 yrs
  - Extrapolating from the local rate, (4-6)/100 yrs
Nuclear equation of state

- Cooling rate depends on assumed nuclear EOS
- \( \rightarrow \) Measure \( \nu \) flux at late times

Pons, Reddy, Prakash, Lattimer, Miralles, astro-ph/9807040
Nucleosynthesis

- It is thought that many heavy elements are made in a core-collapse supernova, in the so-called r-process: Quick absorption of neutrons (faster than $\beta$ decay).
- The neutrino-driven wind in the hot bubble has high entropy per baryon
- Current best models don’t quite work: neutrons combine into $^4\text{He}$
- Several solutions proposed:
  - Faster outflow
  - Create even more entropy
  - Change n/p ratio by changing neutrino fluxes (Qian&Fuller)
- Huge subject, see e.g. G. McLaughlin’s talk at neutrino2006 for further details and refs.
Physics of neutrino decoupling


Thermal Equilibrium

\[ \overline{\nu}_e p \leftrightarrow n e^+ \]
\[ \nu_e n \leftrightarrow p e^- \]

Free streaming

Neutrino sphere (NS)

Scattering Atmosphere

\[ \nu N \leftrightarrow N \nu \]
\[ \nu e \leftrightarrow e \nu \]
\[ N N \leftrightarrow N N \nu \bar{\nu} \]
\[ e^+ e^- \leftrightarrow \nu \bar{\nu} \]

Thermal Equilibrium

Energy sphere (ES)

Diffusion

Transport sphere

graphics courtesy of G. Raffelt
Astrophysics of the explosion

- Spherically symmetric 1-d models do not explode
  - Shock never gets revived

*Convection to the rescue*

- Actual simulations show vigorous turbulence behind the shock front at early times

Snapshot of a 3D simulation at $t=340$ ms by Chris Fryer

Convection essential for the explosion mechanism!

Testing explosion mechanism with ν’s

- It would be great if the neutrino signal could be used to test this key feature of supernova mechanism.
- It can be!
- Late-time signature ($t \gtrsim 3-5$ sec), modification of MSW flavor transformation by the turbulence of the explosion.

“Typical” spectra

- from hep-ph/0412046; after T. Totani, K. Sato, H.E. Dalhed, and J.R. Wilson
**MSW effect in SN: original spectra get permuted**

- Flavor transformations occur for both $\nu$'s and anti-$\nu$'s
- Depend on the type of mass hierarchy

- $\Delta m^2_{atm}$
- $\Delta m^2_{\odot}$
- $\theta_{13}$
- $\theta_{\odot}$

March 24, 2007, U. of Hawaii

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MSW effect in SN: basics

- Flavor transformations for both $\nu$'s and anti-$\nu$'s
- Depend on the type of mass hierarchy

\[ \Delta m^2_{\odot} \]

\[ \Delta m^2_{\text{atm}} \]
Flavor transformations in the first few seconds

- Resonance regions at a few $\times 10^9$ cm, a few $\times 10^{10}$ cm, density profile unperturbed by the explosion.
- This means density gradients in progenitor is very smooth, compared to the neutrino osc. length.
- On resonance, $\lambda_{osc} \sim (\Delta m^2/(2E) \sin^2 \theta)^{-1}$
  - $10^1$ km for $E_\nu \sim 15$ MeV and atm. $\Delta m^2$
  - $\sim 10^{-4}$-$10^{-3}$
- A few $\times 10^2$ km for $E_\nu \sim 15$ MeV and solar. $\Delta m^2$
- $\sim 10^{-4}$-$10^{-3}$
- The L-resonance is guaranteed adiabatic (parameters known).
- Original anti-$\nu_e$ are converted into anti-$\nu_\mu$ and anti-$\nu_\tau$ (and vice versa) -> hotter observed spectrum.
Shock reaches the resonant layer

- At 3-5 seconds, shock reaches the H-resonant layer, while neutrinos are still streaming out of the protoneutron star.
- Shock is very steep (photon mean free path) -> transition changes to maximally nonadiabatic.

Schirato & Fuller, astro-ph/0205390
Predicted signatures at Super-K and megaton water-Cherenkov detector

- from Thomas, Kachelrieß, Raffelt, Dighe, Janka and Scheck, JCAP09, 015 (2004)
Let not forget convection!

- Convection developing during the first second creates large density/velocity fluctuations behind the shock.

“Pulsar Recoil by Large-Scale Anisotropies in Supernova Explosions”
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Turbulent fluctuations persist to later times
Density fluctuations can be important for neutrinos!

- Smooth profile: adiabatic or non-adiabatic

\[ \nu_{\tau}' \equiv \nu_\mu \sin \theta_{\text{atm}} + \nu_\tau \cos \theta_{\text{atm}} \]

- In the “noisy” density profile of the turbulence, a third option: at densities near resonant, neutrinos may undergo “flavor depolarization”.
  - Random walk on a sphere in flavor space
  - Effect known for a long time
    - ... many others
Can’t we just apply existing analytical results in the literature?

- No, we can’t!
- Exist analytical treatments of neutrino evolution in “delta-correlated noise” \( \langle \delta n(x) \delta n(y) \rangle = n_0^2 L_0 \delta(x-y) \)
  - Loreti, Qian, Fuller, Balantekin, Phys. Rev. D 52 6664 (1995)
  - ...

Spin precession in turbulent magnetic field treated nicely in Miranda, Rashba, Rez, Valle, Phys.Rev.D70:113002,2004
Kolmogorov theory of turbulence

- Turbulent fluctuations are not described by the delta-correlated noise.
  - Taken literally, delta-correlated noise \( \langle \delta n(x) \delta n(y) \rangle = n_0^2 L_0 \delta(x-y) \) is unphysical.
  - Even if regularized at small scales in an ad hoc way, no way to connect to large-scale features observed in simulations.

- Rather (Kolmogorov)
  \[ \delta \rho_\lambda \sim \delta \rho_0 (\lambda/r_0)^\beta, \quad \beta \sim 1/3 \]

- Is turbulence seen in realistic simulations strong enough to affect neutrinos?
Adding noise to a smooth profile

- Start with a smooth adiabatic density profile; add Kolmogorov noise; vary normalization.
- Three regimes are clearly seen:
  - Noise negligible
  - Noise perturbative
  - Complete depolarization

adiabatic
Solution and Kolmogorov spectrum

- **For Kolmogorov turbulence**
  \[ C(k) \equiv \int dx \langle \delta n(0) \delta n(x) \rangle e^{-ikx} = C_0 k^{-5/3} \]

  we have

  \[ P_{\text{perturb}} \approx \frac{G_F}{\sqrt{2n'_0}} C_0 \left( \frac{\Delta m^2 \sin 2\theta_{13}}{2E} \right)^{-2/3} \times 0.84 \]

- **This means**
  \[
  P \rightarrow \begin{cases} 
  P_{\text{perturb}}, & P_{\text{perturb}} \ll 1/2, \gamma \gg 1 \\
  1/2, & P_{\text{perturb}} \gtrsim 1/2, \gamma \gg 1 \\
  1, & \gamma \ll 1
  \end{cases}
  \]

  perturb. noise, adiabatic smooth
  large noise, adiabatic smooth
  nonadiabatic smooth

- See astro-ph/0607244 for details
Implications

- Simulations see order one density variations on large scales $r_0 \to$ use to fix $C_0$
- The noise amplitude on small scales turns out to be more than enough to insure complete depolarization by turbulence

$$\frac{\delta n_r}{n_r} > 0.1 \, \theta^{1/3}_{13}$$

so long as the oscillation length stays below the scale height of the smooth component in the bubble (i.e. adiabaticity)
Off-resonance depolarization

- Since on resonance the effect is strongly oversaturated, by continuity expect that it becomes important before the density in the turbulence is diluted down to the resonance value

- The depolarization effect
  - starts setting in earlier, possibly at \(~ 3\) seconds
  - Turns on gradually (more so than the shock effect)

- See astro-ph/0607244 for details
The shadow effect

- Turbulence produces 50/50 incoherent mixture of the two states
- Density matrix $\text{diag}(1/2,1/2)$ commutes with any Hamiltonian -> any other features neutrino encounters, before or after turbulence, have no effect
- Sensitivity to front shock lost, replaced by the signal from turbulence
  
  Fogli, Lisi, Mirizzi, hep-ph/0603033

- Turbulence casts a shadow!
  - If neutrino encounters turbulence at resonant densities and in the absence of the turbulence transition would have been adiabatic, the shadow effect occurs

- At $t \sim 8$ sec the L-resonance also becomes depolarized -> no regeneration in Earth
The shadow effect

- At \( t \sim 8 \text{ sec} \) the L-resonance also becomes depolarized -> no regeneration in Earth

For LMA parameters and SN energies, neutrinos are resonant in the Earth

“Standard” Earth effect from Takahashi, Watanabe, Sato, hep-ph/0012354
(Some) implications

- For neutrino properties:
  - Signal change (lowering of $E_{av}$, broadening of the spectrum, dip in the # of events) will occur *either* in the neutrino or antineutrino channel, indicating the sign of mass hierarchy
  - Lower bound on $\theta_{13}$, at the level of $\sin^2\theta_{13} \gtrsim 10^{-4}-10^{-3}$.

- For understanding supernova physics
  - Observe the turbulence in the expanding hot bubble behind shock in real time -> confirm the key ingredient of the explosion mechanism
  - Spectrum swapping $\nu_e \leftrightarrow \nu_{\mu,\tau}$ will be incomplete -> be careful in inferring original temperatures
  - Signal may (strongly) depend on the direction!

- Others being worked on... Stay tuned!
Summary

- Measuring neutrino signal from next galactic supernova will
  - Test physics BSM
  - Nuclear EOS
  - Neutrino oscillation parameters
    - $\theta_{13}$, hierarchy
  - Astrophysics of the explosion
    - Convection
    - Neutrino transport and spectra formation
    - ...
  - etc, etc ...

Analytical solution, “noisy” resonance

- First, check if the evolution in the absence of the fluctuations would be adiabatic.
- If not, that means that density change is very abrupt, adding turbulence to it doesn’t change the result.
- \( \rightarrow \) if the adiabaticity parameter

\[
\gamma \equiv \frac{\pi (\Delta m^2 \sin 2\theta_{13}/4E)^2}{G_F|dn_0/dr|/\sqrt{2}} < 1
\]

neutrino evolution is unaffected by the noise.

- Adiabaticity fulfilled for \( \sin^2 \theta_{13} \geq 10^{-4}-10^{-3} \).
Analytical solution, “noisy” resonance II

- If $\gamma \gg 1$, the (perturbative) probability of a transition between mass eigenstates is given by

$$P_{\text{perturb}} \sim \frac{G_F}{\sqrt{2n_0'}} \int dk C(k) G\left(\frac{k}{2\kappa}\right) \quad \kappa \equiv \frac{\Delta m^2}{4E} \sin 2\theta_{13}$$

- Here $C(k)$ is a Fourier transform of the correlation function of the noise

$$C(k) \equiv \int dx \langle \delta n(0) \delta n(x) \rangle e^{-ikx}$$

- and the spectral response function $G(p)$ is given by

$$G(p) \sim \frac{\Theta(p - 1)}{p \sqrt{p^2 - 1}} \quad \text{for} \quad \gamma \gg 1$$
General properties of the solution

- The spectral response function $G(2E \frac{k}{\Delta m^2 \sin 2\theta_{13}})$ is peaked at $k \sim \Delta m^2 \sin 2\theta_{13} / 2E$, up to a factor equals to inverse neutrino oscillation length.

- For fluctuations on longer distance scales, the response is approximately zero (exp. suppressed); those fluctuations are followed adiabatically.

- Contributions of fluctuations on shorter scales are power-law suppressed ($\sim k^{-2}$).

- Previously known analytical result for delta-correlated noise $\langle \delta n(0) \delta n(x) \rangle = n_0^2 L_0 \delta(x)$ is correctly reproduced (in the region of applicability $P \ll 1$).