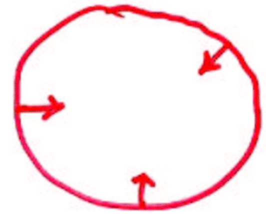
When does ν scattering matter?

1. Supernova
2. Early Universe (but in a rather trivial way – except in deviant theories)
3. Hyperaccreting Black Holes

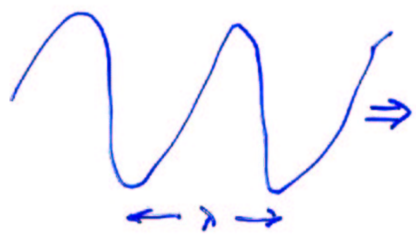
Supernova

Infall



$e^- + \text{nucleus} \rightarrow \nu + \text{nucleus}'$

D. Z. Freedman coherence:



$\Rightarrow$ ● Nucleus

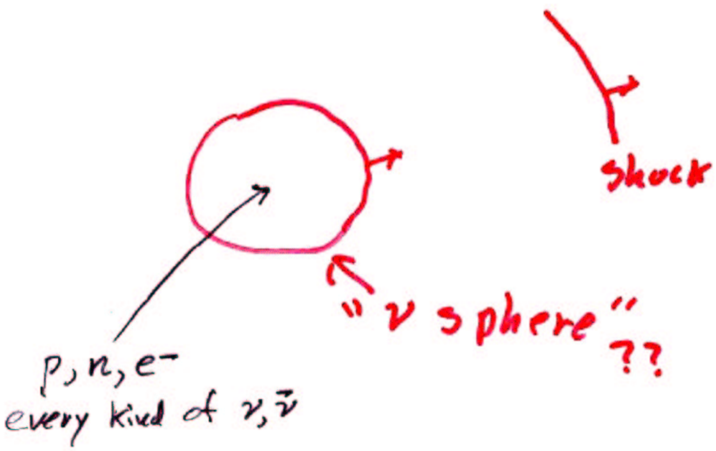
$\lambda > R_{nucleus}$

$$\sigma_\nu \sim N^2 \quad (\text{not } N)$$

At some point $\rho \sim 10^{12}\, g\, c^{-1}$

Neutrinos are trapped. (Mazurek)

After the bounce



Trapped ν_e's and many, many more thermal $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ diffuse out.

Do we care exactly how?

maybe

3

where $x = (E_\nu)(kT)^{-1}$ and where the const. C may be as large as 6×10^{-11}, according to Friman and Maxwell.[5]

We note that, for example, when $kT = 10$ MeV, $E_\nu = kT$ this process is approximately as important as the neutral current process. For lower energies the charged current reaction will dominate. Note in particular that there is no window for low energy electron neutrinos to escape, because of the three body absorption.

Using the neutral current term (9) only for $\lambda(E_\nu)$ we have calculated from (4) the energy flux, $\mathfrak{F}$, which is of the form

$$\mathfrak{F} = \frac{7}{12}\, ac\, T^3\, \frac{\partial T}{\partial r}\, \lambda_{av}(T) \tag{11}$$

where a is the black body constant and λ_{av} is the appropriate energy averaged mean free path. We find

$$\lambda_{av} = \left(\frac{\rho_{nuc.}}{\rho}\right)^{\frac{1}{3}} \left(\frac{kT}{1\ \text{MeV}}\right)^{-3} \times 6\times10^5\ \text{cm} \tag{12}$$

we estimate a cooling time from λ_{av} as

$$\tau_c \approx \lambda_{av}^{-1}(T)\, R^2 c_v (ac)^{-1}\, T^{-3}\, N^{-1} \tag{13}$$

where N is the number of neutrino species. Taking $c_v \approx 10^2 \left(\frac{kT}{1\ \text{MeV}}\right)$ erg/cm^3 $^{\circ}$K as for a free Fermi gas of neutrons at nuclear density we obtain $\tau_c \approx \frac{60\ \text{sec}}{N}$ for $kT = 20$ MeV. The cooling time is directly proportional to temperature.

Let us consider the implications of these results for the complete lepton loss and energy loss scenario for the new neutron star. The initial state of the neutron star, at the time of the core-mantle separation, is one in which the temperature is of the order of 5-10 MeV and the neutrino chemical potential is as high as 100 MeV. At this time most of the excitation energy of the star is still stored mechanically; the star is born in a state of large amplitude radial pulsations. If all of this energy were immediately converted to heat the temperature of the star would rise to around $kT = 80$ MeV. However, .1 second is the minimum time which has been estimated for the damping of the radial pulsations, and some estimates are orders of magnitude greater.

Thus it seems likely that the lepton excess (or neutrino chemical potential) is largely radiated before the

3.5

After 1987a we did a serious Bayesian Statistics estimate of the probable time of the next galactic (or LMC) supernova.

1979 our paper ↑
8 years
1987 ↓

So: 1995!!

(nah - it's 300 years)

The answer to: "Are we interested?"

1. If we get very lucky, then the 8000 events from SN(2004) could tell us plenty;
   - about neutrinos
   - about S.N.

2. The ν physics is needed for working out the dynamics of explosions.

Wilson
Woosley
Burrows
Mezzacappa
Bruenn
Janka
others
Fryer

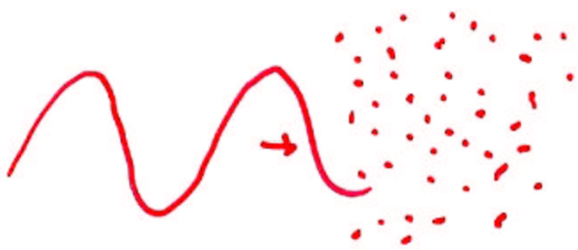
3. R process nucleosynthesis depends on detailed features of the pulse and (possibly) on ν flavor-oscillation physics as well. (G. Fuller)

Physics of ν's in a medium:

scattering, absorption, emission

(think.. nucleons + ν's)

Coherent effects



when $\lambda >$ (interparticle spacing)

Γ = scat. rate $\neq \sigma n$

Example:

if $H_I = G_F \int \psi_\nu^\dagger(x)\, \psi_\nu(x)\, n(x)\, d^3x$

(n = neutron # density)

Then:

$$\Gamma_{\lambda\ \mathrm{large}} = \frac{n\, \sigma_0\, T}{\partial P/\partial n}$$ From equation of state

Note: for free Boltzmann gas

$$P = nT$$

$$\Gamma = n\sigma_0$$

But for interacting gas, the scattering rate is different.

Repulsions $\Rightarrow$ decrease

Attractions $\Rightarrow$ increase

(Eqn. of state is all you need)

HOWEVER:

$\sim \frac{3}{4}$ of ν scat. is "Gamow-Teller"

$$H_I = G_F \int dx\, \bar{\Psi}_\nu(x) \gamma_i (1-\gamma_5) \Psi_\nu(x)\, M_i(x)$$

where $M_i(x) = \Psi_N^\dagger(x)\, \sigma_i\, \Psi_N(x)$

Now we have,

$$\Gamma^{G.T.}_{\text{large } \lambda} = \frac{\sigma_0 T}{\partial F / (\partial m_3)^2}$$ how to find??

F = Free energy /vol

In the case of degenerate nucleons,
the nuclear matter in big nuclei
provides a clue.

Giant G-T resonance parameters

$\Rightarrow$ A BIG SUPPRESSION IN $\Gamma_{G.T.}$

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More complete treatment of ν
scattering, emission, absorption

Neutral Current: $\nu, \bar{\nu}$ (all flavors) $\rightarrow \nu, \bar{\nu}$

Fermi: Γ = (Kinematical factors) $\times$

$$\frac{1}{Z} \text{ Fourier Trans} \Big[\underbrace{Tr\left[e^{-\beta[H - \mu_i N_i]} M(x,t) M(0,0) \right]}_{\text{density correlator}} \Big]$$

G.T.:

$$M(x,t)\, M(0,0) \rightarrow M_i(x,t) M_j(0,0)$$

Charged current: for $\nu_e + n \leftrightarrow e^- + p$, etc.

$$M(x,t)\, M(0,0) \rightarrow M_+^\dagger(x,t)\, M_+(x,0)$$

where $M_+ = \Psi_p^\dagger \Psi_n$

9.

The venerable Ring Approx.

1. Extends the results to shorter wavelengths.

2. Long wavelength limit as before.

3. Absorption, emission, scattering of ν's reduced by around a factor of two in the region $\rho = 10^{13} - 10^{14}\ g\,c^{-3}$

Less total scattering rate, but a lot more inelasticity in neutral-current scatt.

(Important for equilibration of $\nu_\mu + \nu_\tau$)

Done of this is in the codes, as yet

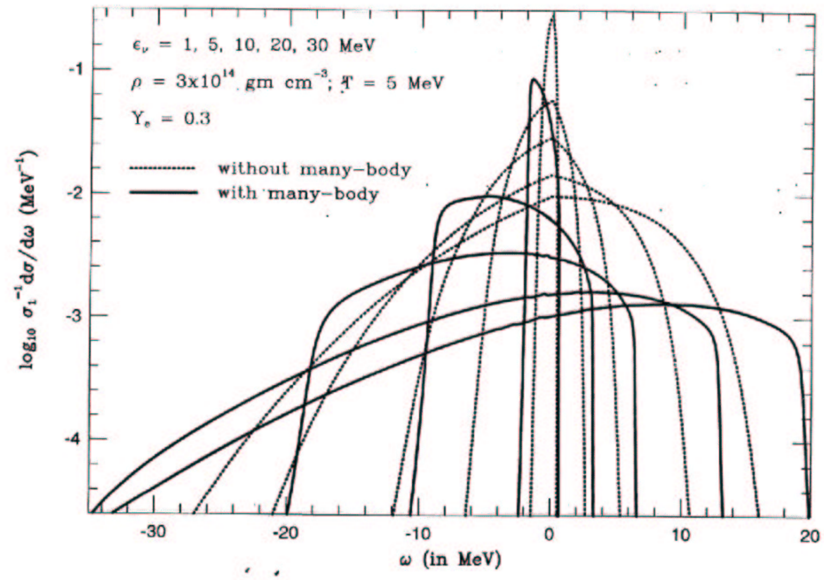


FIG. 3. The $\log_{10}$ of the differential cross section for ν–nucleon scattering versus the energy transfer, ω, for various values of the incident neutrino energy (ϵ_ν = 1, 5, 10, 20, 30 MeV). The dashed curves neglect the many–body effects associated with m^* and $C_{V,A}$, while the solid curves include them. A density of 3×10^{14} gm cm^{-3}, a temperature of 5 MeV, and an electron fraction, Y_e, of 0.3 were assumed. The curves were normalized to the total ν–nucleon scattering cross section without nucleon blocking or many–body effects.

Not in codes.

Burrow's & Thompson will eventually include in a SN calc.

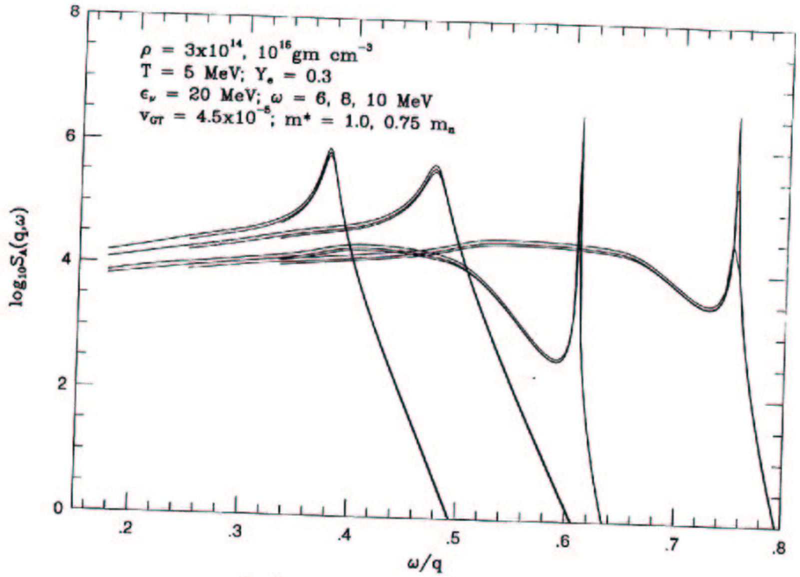
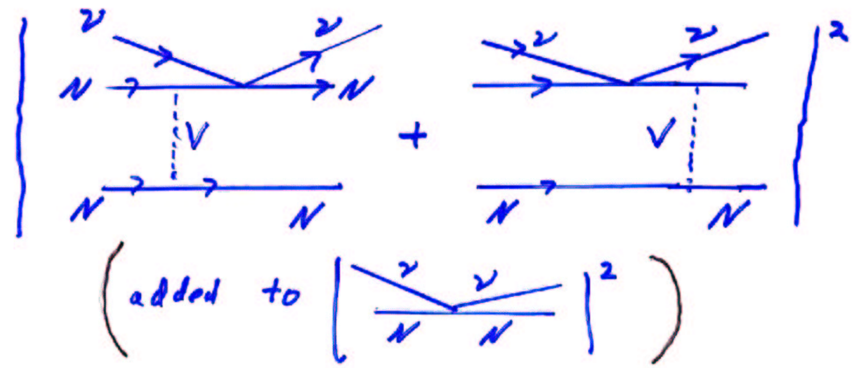


FIG. 2. Log_{10} of the Gamow–Teller structure function versus ω/q for an incident neutrino energy of 20 MeV, energy transfers, ω, of 6, 8, and 10 MeV, two values of the effective mass ($m^* = [0.75m_n, 1.0m_n]$) and two values of the density ($\rho = 3 \times 10^{14}$ and 10^{15} gm cm^{-3}). A temperature of 5 MeV and a Y_e of 0.3 were used, as was the default v_{GT} ($= 4.5 \times 10^{-5}$).

30

12

Even worse:



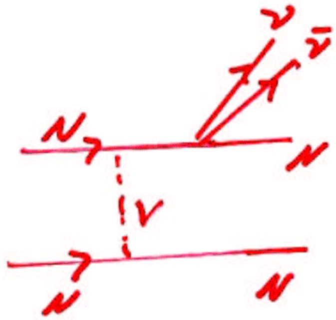
"It's another channel – so it increases the rate"

What's wrong with this?

1. We already know that corrections are to big to do a straight perturbation calculation.
2. Moreover, failure to keep states normalized results in the answer being wrong (and having the wrong sign) even to the indicated order in perturbation theory.
3. All such stuff is subsumed in earlier calculation of reduction, anyway.

and then:

"We put in bremsstrahlung of $\bar{\nu}\nu$"



Grossly overestimated!

Conclusions:

1. "DOES IT EXPLODE ?"

2. "DOES IT SUSTAIN THE R PROCESS ?"

3. " HAVE YOU PUT IN ....

Bremsstrahlung ?

Paul: ?

ν-ν scat ?

correlations ?

? "

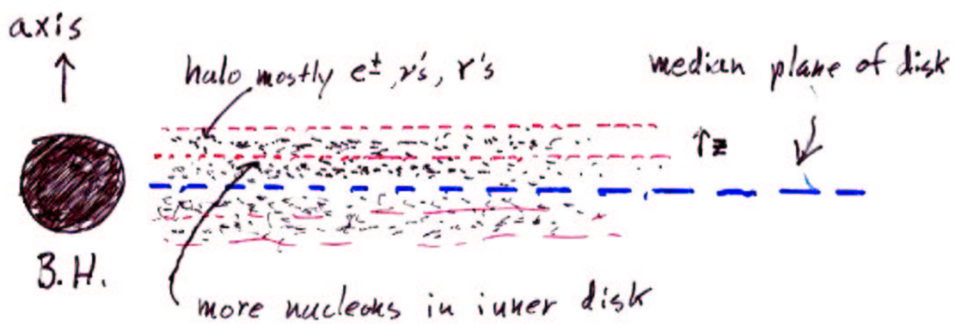
"can't we do the physics first ?"

"take away their power points"

On a brighter note:

Another venue for neutrino transport

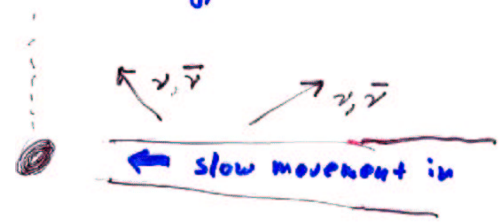
(Hyper) Accretion Disk



Tidal (grav) force ~ z (height)

Neutrino Opaque!!

Energy radiated in ν's



and energy is advected by BH.

Toy model

1. local heating ~ $M_{nucleon}$ × shear rate
2. Solve Boltzmann eqn to find outgoing ν flux + internal temperatures. (opacity dominated by rel. particles)
3. Hydrostatic equilibrium. (where pressure gradient comes from #2)

$\Rightarrow$