Electron Flavor Neutrinos in Stellar Core Collapse and Postbounce Evolution

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- How to visualize the neutrino production sites/rates calculated with detailed general relativistic Boltzmann neutrino transport?
- Let's try: Stellar core collapse and postbounce evolution in a movie with neutrino production sites/rates...
- Improvements of weak interaction rates at these sites and their effect to the fluid dynamics.
- Only unphysical opacity reductions lead to explosions in 1D; however, all neutrino-driven explosions show $Y_e>0.5$ in the innermost layers of the ejecta.

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Paths of Research

accuracy and refinement →

Comprehensiveness ↓

	Idea	Plausibility	Proof
spherical symmetry	Colgate & White 66 important role of neutrino Bethe & Wilson 85 delayed mechansim Baron et al. 85 soft EoS and GR	May & White 67 relativistic hydrodynamics Burrows & Goshy 93 stationary analytical model Janka 00 time-dependent analytical model Myra & Bludman 89 GR and neutrino-electron scattering Swesty et al 94 influence of EoS Bruenn et al. 01 GR and MGFLD	Arnett 71 MGFLD Bowers & Wilson 82 MGFLD Bruenn 85 MGFLD Mezzacappa & Bruenn 93 stationary Boltzmann transport Burrows et al. 00 stationary Variable Eddington Factor tran. Rampp & Janka 01/02 Variable Eddington Factor transport Liebendörfer et al. 01/02 GR Boltzmann transport
hydrodynamic instabilities	Herant et al. 92 convection Miller et al. 93 convection Wilson & Mayle 93 neutron finger convection	Burrows et al. 95 convection with grey neutrino tran. Janka & Müller 96 parameter study for convection Keil et al. 96 protoneutron star convection Mezzacappa et al. 98 convection with multi-group tran.	Ray-by-Ray multi-group transport & multidymensional hydrodynamics ?
MHD +	LeBlanc & Wilson 70 rotation and MHD	Fryer & Heger 00 rotation and convection MacFadyen & Woosley 99 MHD jets Wheeler et al. 00 MHD jet phenomenology	code documentation code testing reproduceability --> experiment

Boltzmann Neutrino Transport

(Rampp and Janka, Mezzacappa et al., Liebendörfer et al.)

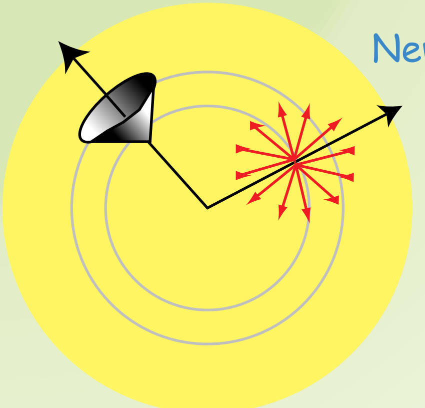
ApJL 539 (2000), PRL 86 (2001), PRD 63 (2001)

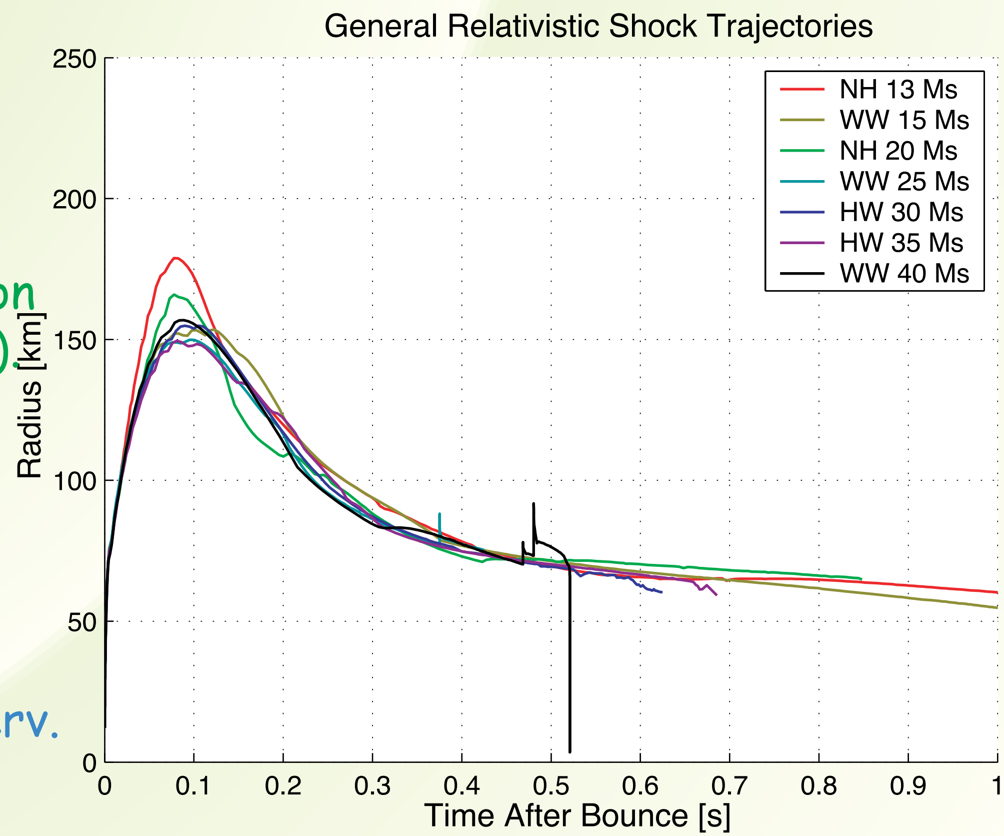
AGILE-BOLTZTRAN

e-flavour
Newtonian+O(v/c)

standard physics
Newtonian+O(v/c)

standard physics,
general relativistic





Direct calculation of the distribution function f(time,radius,angle,energy).
Dimensionality:

- ~30'000 time steps
  102 adaptive mass zones
  6 propagation angles
  12 energy groups
- GR dynamics and energy conserv.
- GR redshift
- GR light bending

Statistics of Escaping Neutrinos

L(in) → [emission / absorption] → L(out)

L(out) = L(in) + emission - absorption

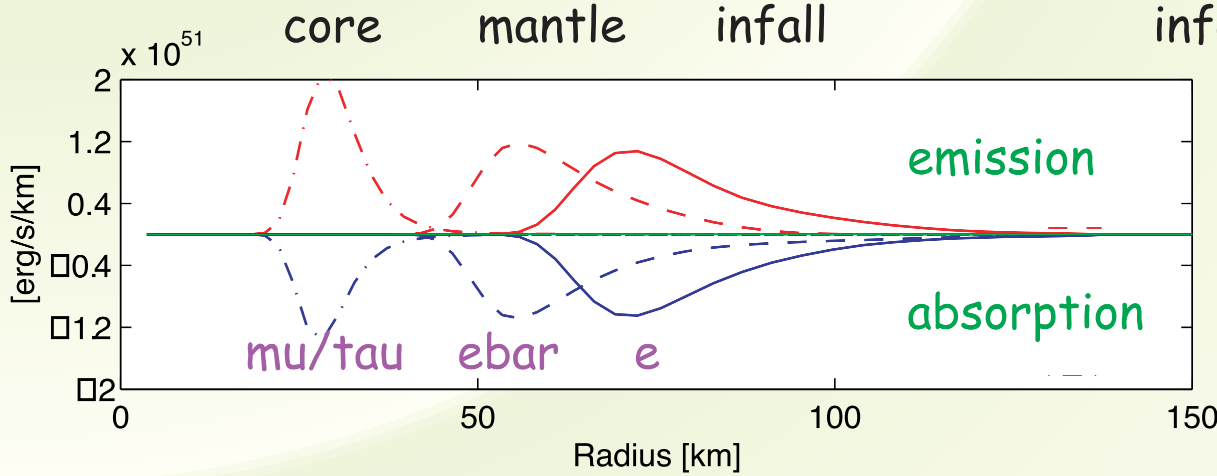
L(out) = x L(in) + emission

resolve for attenuation x = ...

Radius

emission1	+ emission2	+ emission3	+ emission4	+ emission5	= L(surface)
*x2*x3*x4*x5	*x3*x4*x5	*x4*x5	*x5		

cold core — hot mantle mantle — slow infall — shock — fast infall

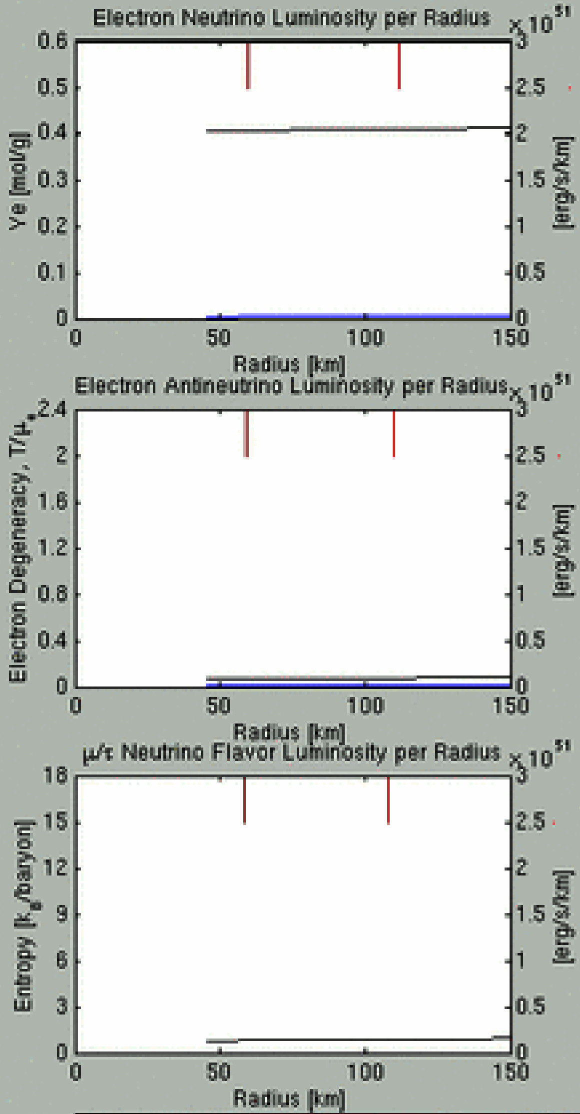


window = neutrino type

area = luminosity

location = production site

colour = energy group



Time after bounce = -27.4901 ms

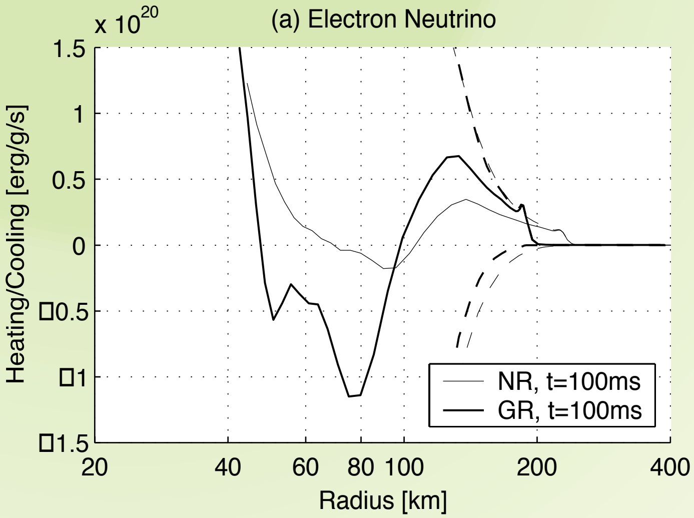
These graphs show the luminositiy per radius of escaping neutrinos as a function of radius. The shaded area is proportional to the total luminosity. The color indicates the contribution from individual energy groups according to the legend. This graph shows the electron neutrino luminosity and the electron fraction profile, Ye. As matter falls in, a drop in Ye is coincident with electron capture and electron neutrino emission. At the neutrino burst, large luminosities stem from a very narrow radius interval.

The tracers at the top of the graphs indicate the position of the neutrinospheres for different neutrino energies according to the legend. The tracers at the bottom mark density decades in log(g/cm^3). This graph shows electron anti-neutrino luminosities. The blue lines separate contributions from positron capture, white lines refer to the pair process. The electron degeneracy is shown as additional profile because both processes strongly depend on the positron abundance. The data belong to the evolution of a Woosley & Weaver 15 solar mass progenitor in general relativistic spherically symmetric space-time.

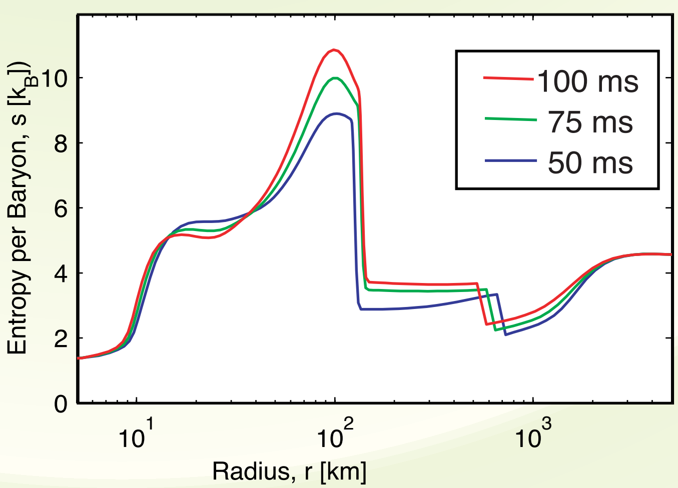
This graph shows the production site of the heavy neutrinos together with an entropy profile. Due to the absence of charged current interactions the production site is deeper in the core than the scattering-dominated neutrinospheres. The neutrinos lose part of their initial rms energy by scattering on electrons before escaping the star at the neutrinospheres. Without protoneutron star convection, the cooling becomes very local at late times.
(ML, 11/2002)

Convective Turnover in the Heating Region

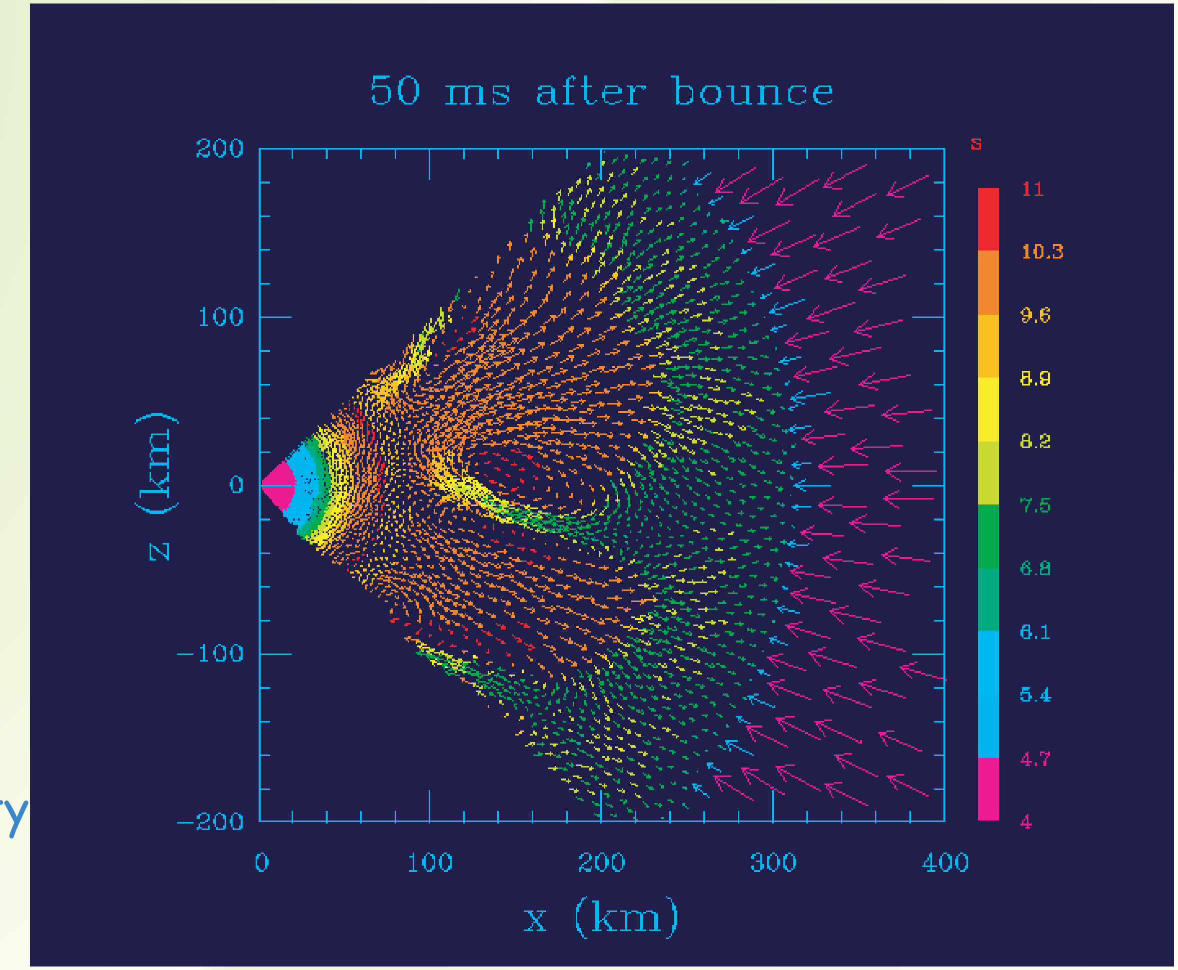
Neutrino heating is strongest at the base of the gain region:



The negative entropy gradient leads to hydrodynamical instability



1D GR simulations very pessimistic!



(Herant et al., ApJ, 1994)

- grey transport (Miller, Wilson & Mayle, 1993)
- grey transport (Burrows, Hayes & Fryxell 1995)
- parameter study (Janka & Mueller, 1996)
- energy dependent imported neutrino transport (Mezzacappa et al., 1998)

Conclusions

Simulations of the mechanism:

- accurate neutrino transport in GR, very restricted spatial dimensionality — no explosions
- 2D simulations (recently even 3D, Fryer & Warren '02), very restricted neutrino transport — explosions
- combinations of 1D transport and 2D hydro — detailed energy spectrum important

Input physics:

- important improvements to standard suggested, ~10% effects on results, no changes in 1D failures
- qualitative changes needed (e.g. protoneutron star convection)

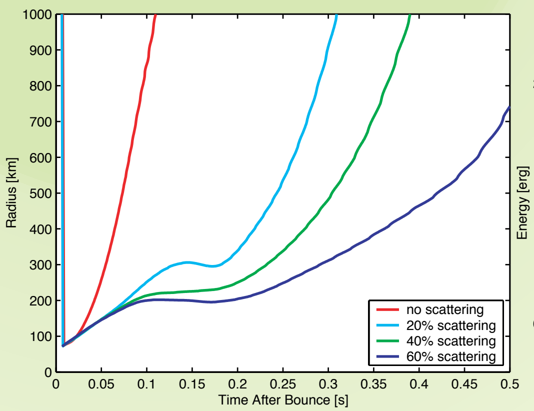
Interaction with ejecta:

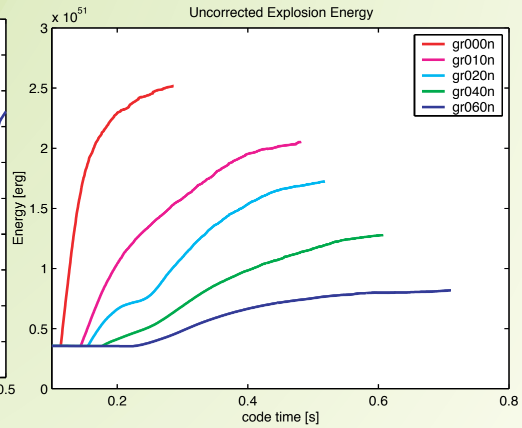
- interaction with hot dissociated and expanding gas leads to high electron fraction in ejecta (partially Ye>0.5)
- nucleosynthesis calculations should be updated to include self-consistent weak interactions between the collapse of the progenitor and the ejection of the outer layers.

High Electron Fraction at the Inner Boundary of Ejecta

Explosions of 20 solar mass of Nomoto & Hashimoto forced with
- lowest angular resolution in neutrino transport (efficient & overestimates heating)
- parametrized scattering of neutrinos on free nucleons (0%-60%)

--> still self-consistent in the sense of energy and lepton number conservation



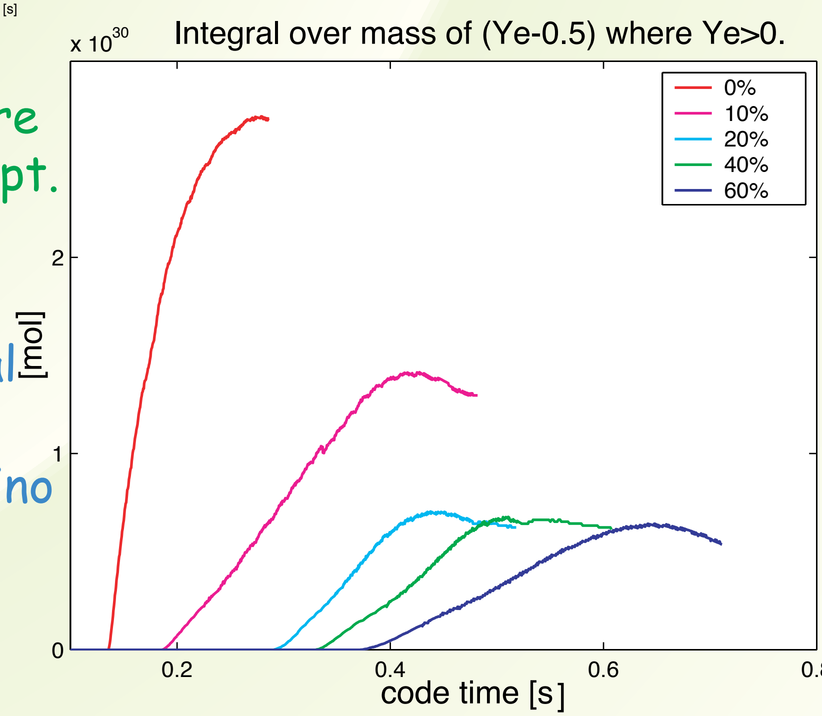


As the electron degeneracy becomes removed in the neutrino heated expanding ejecta, the electron fraction exceeds 0.5, driven by the mass difference between neutron and proton.

Balance between
- electron capture/neutrino capture
- positron capture/antineutrino capt.

Ye up	Ye down
proton/neutron mass difference wins in heated & expanding dis-sociated matter	electron chemical potential higher antineutrino rms energies

(see also Thompson, Burrows, & Meyer 2001)



The high Ye>0.5 in the innermost ejecta seems to be a robust feature in exploding neutrino-driven models

Interaction Physics Extensions

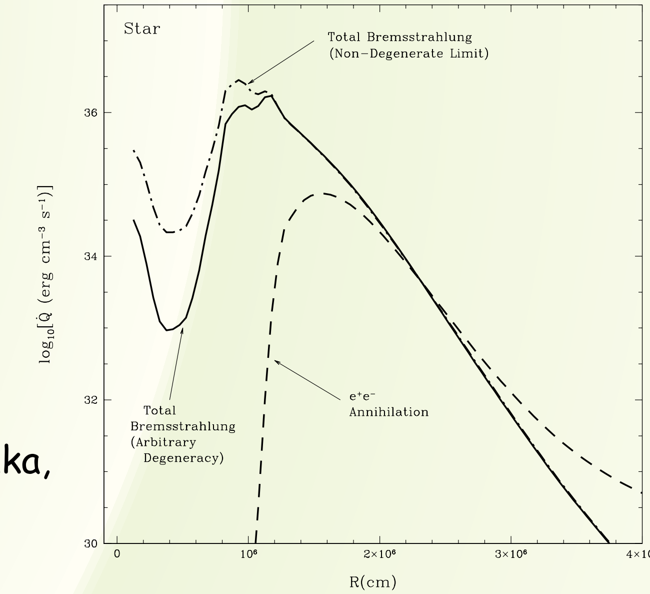
from Horowitz, Phys. Rev. D65, 2002:

Table II Corrections to Opacities

	Correction
1.	Phase space
2.	Matrix element
	a. recoil
	b. weak magnetism
	c. form factors
	d. strange quarks
3.	Pauli blocking
4.	Fermi/thermal motion of initial nucleons
5.	Coulomb interactions
6.	Mean field e ects
7.	NN Correlations in RPA
8.	NN Correlations beyond RPA
9.	Meson exchange currents
10.	Other components such as hyperons
11.	Other phases such as meson condensates or quark matter
12.	Corrections from superfluid/ superconductor pairing
13.	Nonuniform matter
14.	Magnetic field e ects

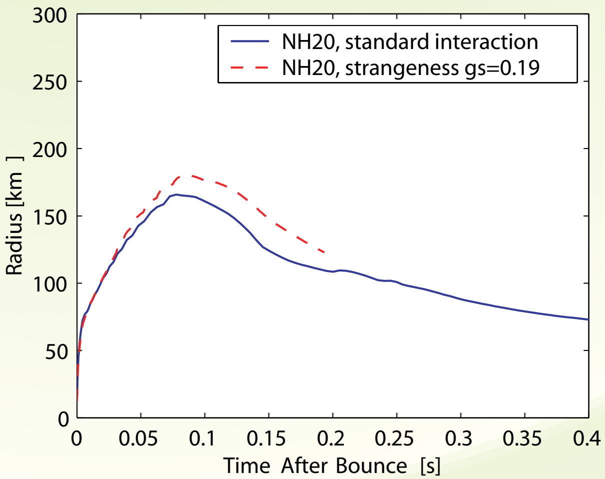
electron flavor annihilation --> mu/tau flavor pair

Keil, Raffelt, & Janka, astro-ph/0208035



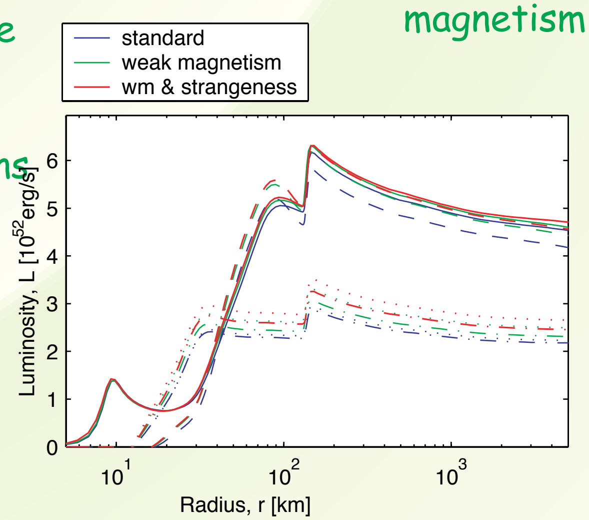
Brems-strahl-lung, nucleon recoil

Thompson, Burrows, & Horwath Phys. Rev. C62 (2002)

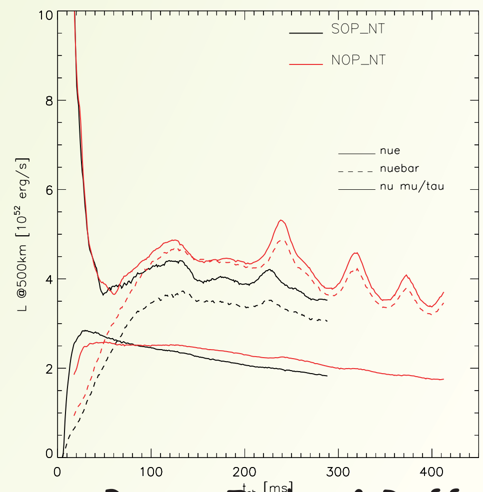


Liebendörfer et al., astro-ph/0203260

strange quarks in the nucleons



weak magnetism



Rampp, Buras, Janka, & Raffelt astro-ph/0203493

Electron Flavor Neutrinos in Stellar Core Collapse and Postbounce Evolution

M. Liebendörfer*, O. E. B. Messer†, A. Mezzacappa‡, G. Martinez-Pinedo§, W. R. Hix¶, and F.-K Thielemann‖

Self-consistent spherically symmetric supernova simulations try to address a neutrino-driven supernova mechanism [1]. Recently, neutrino transport has been brought close to perfection in the solution of the dynamic Boltzmann transport equation [2] and general relativity has been included [3] with "standard" nuclear and weak interaction physics to form the current state-of-the-art in spherically symmetric simulations. The qualitative result that neutrinos don't drive a supernova in spherical symmetry has been corroborated. There is broad agreement that convectional instabilities behind the outwards propagating shock increase the heating efficiency. While multi-dimensional simulations with neutrino transport approximations delivered encouraging results [4], more recent calculations, combining the values of one-dimensional energy dependent transport with two-dimensional hydrodynamics, again failed to explode the stellar envelope [5]. Sending the light of arbitrarily selected simulations of stellar core collapse and postbounce evolution through prisms that project along accuracy and refinement on the one hand, and comprehensiveness on the other hand, we find darkness in the refined *and* comprehensive corner, where a thorough understanding of the supernova mechanism remains hidden.

In order to exploit the details of our spherically symmetric calculations with AGILE-BOLTZTRAN [6], we present a movie with the energy-resolved neutrino emission as a function of radius in units of [erg/s/km]. To filter out the relevant contributions within the huge emissivity scale differences, only neutrinos that escape the star are considered. Hence, the shaded area under the line in the graphs is roughly proportional to the total luminosity at all times. After collapse, when the bounce shock rushes outwards through the neutrinospheres, intense emission from electron capture in a narrow region behind the shock forms the electron neutrino burst. Later, in the neutrino heating phase, emission occurs from a broader range. The main production sites are staggered in radius according to neutrino energy and flavor. The emanating electron flavor neutrinos are in close interaction with the infalling matter in the cooling region above the neutrino sphere: the matter locally reaches thermal balance and weak equilibrium. Further out, where matter has just passed the shock, its temperature is below balance and its electron

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fraction above equilibrium. Adjustments occur during the short infall time through the heating region, though not enough for a shock revival in stratified hydrodynamics.

The failed supernova models in spherical symmetry have triggered many suggestions how to improve the input physics. We point to recent investigations and find that important improvements can be made. However, the overall influence to self-consistent simulations is in most cases on a quantitative scale of order 10%, quite far from the order of magnitude where corrections would revive the hope to obtain explosions in general relativistic spherically symmetric space-time. Nevertheless, it is interesting to parametrize the input physics beyond physical limits and to explore the phenomenology of neutrino-driven explosions with detailed neutrino transport. All our artificially exploding models produce an electron fraction above 0.5 in the neighborhood of the masscut. As the material at the mass cut is heated and expanded, the electrons become non-degenerate and the electron chemical potential μ_e falls below the neutron to proton mass difference Q. Rising electron fractions approaching 0.5 have already been predicted in the protoneutron star wind [7]. Here at the base of our high entropy bubble, thermal balance and weak equilibrium favor the tighter bound protons over neutrons. If supernovae are neutrino-driven, significant changes in the electron fraction should not be neglected in future evaluations of supernova nucleosynthesis.

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