Probing the Equation of State
with
Neutrinos from Core-collapse Supernovae (?)

Tobias Fischer
University of Wrocław, Poland

“Dense Phases of Matter”
INT Workshop, Seattle WA, July 2016
**Wrocław**: 3rd largest city in Poland, located in the heart of Europe.
Wrocław is at the south-west end of Poland, 100 miles away.
~600,000 people living here.
7 Nobel Prize winners:

1. Theodor Mommsen (1817-1903)  
   1902 (literature)
2. Phillip Lénàrd (1862-1947)  
   1905 (physics)
3. Eduard Buchner (1860-1917)  
   1907 (chemistry)
4. Paul Ehrlich (1854-1915)  
   1908 (medicine)
5. Gerhart Hauptmann (1862-1946)  
   1912 (literature)
6. Fritz Haber (1868-1934)  
   1918 (chemistry)
7. Max Born (1882-1970)  
   1954 (physics)
Contents:

• Motivation
• Modeling core collapse supernovae
• Supernova phenomenology
• Equation of state dependence of the neutrino signal
• Summary
A neutron star is born in a core-collapse supernova explosion as hot & lepton-rich protoneutron star (PNS).

PNSs develop (deleptonize & cool) towards neutron stars via the emission of neutrinos of all flavors for about 10–30 s.

Some insights from SN1987A:

\[ E_{\text{expl}} \sim 10^{51} \text{ erg} , \quad E_{\nu} \sim 3 \times 10^{53} \text{ erg} \]

All current supernova models (that include “accurate” neutrino transport !!!) are in agreement with SN1987A.
Neutrino detection – current and future

Local Group of Galaxies

With megatonne class (30 x SK)
60 events from Andromeda

Current best neutrino detectors sensitive out to few 100 kpc
Supernova equation of state

Conditions:

\[ T \approx 10^{-2} - 50 \text{ MeV} \]
\[ \rho \approx 0 - 2 \times n_0 \]
\[ Y_e \approx 0.01 - 0.6 \]

(charge fraction/density)

Extends beyond a “simple” relation between pressure and energy

Nuclear clustering; \(^2\text{H}, \, ^3\text{H}, \, ^3\text{He}, \, ^4\text{He}\)

Mott-transition to homogeneous phase

Nuclear medium modifies nucleon properties/nuclear masses (binding energy shifts)

Modeling core-collapse supernovae
Core-collapse supernova converts iron-core of massive star into proto-neutron star

Binding energy gain available in form of neutrinos of all flavors

Strong gravity of PNS requires general relativity

\[ \Delta E_G \simeq 3 - 6 \times 10^{53} \ \text{erg} \rightarrow (\nu_e, \bar{\nu}_e, \nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau}) \]

\[ G_{\mu\nu} = R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} = 8\kappa T_{\mu\nu} \] (Einstein equation)

\[ ds^2 = -\alpha(t,a)^2 dt^2 + \left( \frac{r'(t,a)}{\Gamma(t,a)} \right)^2 da^2 + r(t,a)^2 d\Omega \]

<table>
<thead>
<tr>
<th>matter</th>
<th>microphysics</th>
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<tbody>
<tr>
<td>( T^{tt} = \rho(1+e) + J )</td>
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<tr>
<td>( T^{ta} = T^{at} = \rho H )</td>
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<td>( T^{aa} = p + \rho K )</td>
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<tr>
<td>( T^{\theta\theta} = T^{\phi\phi} = p + \frac{1}{2}\rho(J - K) )</td>
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Misner & Sharp (1964) PhyRev.136, 571
Neutrino transport

Neutrinos are light-like geodesics in curved spacetime; massless ultra-relativistic particles.

\[ F_\nu (t, \bar{x}, \bar{v}) \rightarrow F_\nu (t, a, \mu = \cos \theta, E) = \frac{f_\nu (t, a, \mu, E)}{\rho} \]

\[ dN_\nu = F_\nu (t, a, \mu, E) E^2 \, dE \, d\mu \, da \]

\[ \frac{\partial F}{\partial \alpha \partial t} (\mu, E) = -\frac{\mu}{\alpha} \frac{\partial}{\partial \alpha} \left( 4\pi r^2 \alpha \rho F \right) \]

\[ - \Gamma \left( \frac{1}{r} - \frac{1}{\alpha} \frac{\partial \alpha}{\partial r} \right) \frac{\partial}{\partial \mu} \left[ (1 - \mu^2) F \right] \]

\[ - \left( \frac{\partial \ln \rho}{\alpha \partial t} + \frac{3u}{r} \right) \frac{\partial}{\partial \mu} \left[ \mu (1 - \mu^2) F \right] \]

\[ + \mu \Gamma \frac{1}{\alpha} \frac{\partial \alpha}{\partial r} \frac{1}{E^2} \frac{\partial}{\partial E} \left( E^3 F \right) \]

\[ - \left[ \frac{\mu^2}{E^2} \left( \frac{\partial \ln \rho}{\alpha \partial t} + \frac{3u}{r} \right) - \frac{u}{r} \right] \frac{1}{E^2} \frac{\partial}{\partial E} \left( E^3 F \right) \]

\[ + \left. \frac{\partial F}{\partial \alpha \partial t} \right|_{\text{coll}} (\mu, E) \]


Doppler shift and the angular aberration between adjacent comoving observers for \( \mu \neq 0 \)

red/blueshift spectra

Collision integral

\[ \left. \frac{\partial F}{\partial t}(\mu, E) \right|_{\text{collision}} = j(E) \left( \frac{1}{\rho} - \frac{1}{\lambda(E)} \right) F(\mu, E) \]

emissivity \hspace{1cm} opacity/absorptivity

Charged current

\[ e^- + p \leftrightarrow n + \nu_e \]
\[ e^- + \langle A, Z \rangle \leftrightarrow \langle A, Z - 1 \rangle + \nu_e \]

Juodagalvis et al. (2010), NPA 848, 454

\[ e^+ + n \leftrightarrow p + \bar{\nu}_e \]
Collision integral

\[
\frac{\partial F}{\partial \alpha t}(\mu, E)\bigg|_{\text{collision}} = j(E) \left(\frac{1}{\rho} - F(\mu, E)\right) - \frac{1}{\lambda(E)} F(\mu, E) \\
+ \frac{1}{c} \frac{E^2}{(hc)^3} \int d\mu' R_{\nu N}(\mu', \mu, E) F(\mu', E) - \frac{1}{c} \frac{E^2 F(\mu, E)}{(hc)^3} \int d\mu' R_{\nu N}(\mu', \mu, E) \\
+ \frac{1}{c} \frac{E^2}{(hc)^3} \left(\frac{1}{\rho} - F(\mu, E)\right) \int d\mu' dE' E'^2 R^{\text{IN}}_{\nu e \pm}(\mu, \mu', E, E') F(\mu', E') \\
- \frac{1}{c} \frac{E^2}{(hc)^3} F(\mu, E) \int d\mu' dE' E'^2 R^{\text{OUT}}_{\nu e \pm}(\mu, \mu', E, E') \left(\frac{1}{\rho} - F(\mu', E')\right)
\]

Charged current

\[
e^- + p \leftrightarrow n + \nu_e \\
e^- + \langle A, Z \rangle \leftrightarrow \langle A, Z - 1 \rangle + \nu_e
\]

Juodagalvis et al. (2010), NPA 848, 454

\[
e^+ + n \leftrightarrow p + \bar{\nu}_e
\]

pair reactions

\[
e^- + e^+ \leftrightarrow \nu + \bar{\nu} \\
N + N \leftrightarrow N + N + \nu + \bar{\nu} \quad (N = n, p, )
\]


\[
\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}
\]

\[
\langle A, Z \rangle^* \leftrightarrow \langle A, Z \rangle + \nu + \bar{\nu}
\]


TF. et al. (2013), PRC 88, 065804

scattering

\[
\nu + N \leftrightarrow \nu + N \quad (N = n, p) \\
\nu + \langle A, Z \rangle \leftrightarrow \nu + \langle A, Z \rangle
\]

\[
\nu + e^{\pm} \leftrightarrow \nu + e^{\pm}
\]
Neutrino opacity and EoS

$\nu_e + n \rightarrow e^- + p$

Here: $S_V = S_A \equiv S(q_0, q)$
(density and spin response functions)

$$1/\lambda(E_{\nu_e}) = \frac{G_F^2 V_{ud}^2 (g_V^2 + 3 g_A^2)}{\pi \hbar c} \int \frac{d^3 p_e}{(2\pi \hbar c)^3} (1 - F_e(E_e)) S(q_0, q)$$

$q_0 = E_\nu - E_e , \quad q = p_\nu - p_e$

$$S(q_0, q) = 4\pi \int \frac{d^3 p_n}{(2\pi \hbar c)^3} \delta(q_0 + E_n - E_p) f_n(E_n) (1 - f_p(E_p))$$

$$E_n = \frac{p_n^2}{2m_n^*} + m_n^* + U_n$$

$$U_n - U_p \propto S^F(T, \rho)$$

Charged-current absorption; nucleons are not free gas

Lowest order medium modification of the weak rate; depends on the EoS (symmetry energy):

Roberts et al., (2012) PRC 86, 065803
Horowitz et al., (2012) PRC 86, 065806
Martinez-Pinedo & TF et al., (2012) PRL109, 251104

Reddy et al., (1998) PRD 58, 013009
Core-collapse supernova phenomenology
Stellar core collapse

\[ Y_e = \frac{n_p}{n_B} \]

\[ (Y_e < 0.5 : \text{neutron excess}) \rightarrow M_{\text{core}} > M_{\text{Ch}} \approx 1.44 \left( \frac{Y_e}{0.5} \right)^2 M_{\odot} \]

\[ (Y_e > 0.5 : \text{neutron deficient}) \]

Implosion of the stellar core due to pressure loss; triggered from e\(^-\) captures on protons bound in nuclei

\[ e^- + ^{56}\text{Mn} \rightarrow ^{56}\text{Fe} + \nu_e \]

\[ e^- + ^{56}\text{Co} \rightarrow ^{56}\text{Ni} + \nu_e \]

......

\[ e^- + \langle A, Z \rangle \rightarrow \langle A, Z - 1 \rangle + \nu_e \]

Collapsing stellar core neutronizes; electron fraction drops; collapse proceeds adiabatically/ supersonically

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\( e^- + \langle A, Z \rangle \rightarrow \langle A, Z - 1 \rangle + \nu_e \)

Collapsing stellar core neutronizes; electron fraction drops; collapse proceeds adiabatically/supersonically

Neutrino signal – infall phase

\begin{equation}
\langle A, Z \rangle^* \rightarrow \langle A, Z \rangle + \nu + \bar{\nu}
\end{equation}

TF et al.,(2013) PRC 88, 065804

**Supernova shock**
propagation across the sphere of last inelastic scattering (ν-sphere)

**ν\textsubscript{e}**–deleptonization burst is
**generic feature**

charged current reactions

\begin{align*}
e^- + p & \iff n + \nu_e \\
e^+ + n & \iff p + \bar{\nu}_e
\end{align*}
Supernova evolution in a nutshell

Collapse halts at saturation density where the core bounces back with the formation of shock wave

Rapid shock acceleration to radii of about 100–200 km

Still gravitationally unstable outer layers of the stellar core; stellar collapse continues

Shock stalling due to energy losses – no prompt explosions

Later evolution determined from energy-balance due to:

(a) ram pressure from mass accretion; infalling material ahead of shock

(b) energy liberation (transport) deposition behind accretion shock
Neutrino signal – post-bounce

charged current reactions
\[ e^- + p \leftrightarrow n + \nu_e \]
\[ e^+ + n \leftrightarrow p + \bar{\nu}_e \]

pair processes
\[ e^- + e^+ \leftrightarrow \nu + \bar{\nu} \]
\[ N + N \leftrightarrow N + N + \nu + \bar{\nu} \]
\[ \nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau} \]

elastic scattering
\[ \nu + N \leftrightarrow \nu' + N \]

inelastic scattering
\[ \nu + e^\pm \leftrightarrow \nu' + e^\pm \]

Neutrino-energy hierarchy reflects strength of coupling to matter
Triggering the explosion onset

**General concept:** Energy liberation from central protoneutron star (PNS) to standing shock

Continuous energy deposition that drives shock to increasingly larger radii
(timescale: ~100 milliseconds)

Ejection of the stellar mantle; leaves *bare* PNS behind

---

*A massive hypergiant star as the progenitor of the supernova SN 2005gl*

“...was a single star and that it indeed vanished following the explosion of SN 2005gl... On the basis of its luminosity, such a star is likely to be an extreme member of the group of luminous blue variable stars (LBVs), which are thought to be very massive (>50 M\(_{\odot}\)) short-lived stars.”

---

Neutrino heating (& cooling):

\[ E_v = 3 - 6 \times 10^{53} \text{ erg (available)} \]
\[ E_{\text{expl}} \sim 10^{50} - 10^{51} \text{ erg} \]
(kinetic energy of ejecta)


---

**Alternative scenarios:**

**Magnetic fields**

**Sound waves**

**High-density phase transition**
(Sagert & TF et al., (2009) PRL 102, 081101)
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Sound waves

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Neutrino-driven supernova success stories

  (2D, energy- and angle-dependent neutrino transport; ray-by-ray approximation)
  (9.6, 11.2, 15, 27 $M_\odot$)

  (static field, angle- and energy-dependent Boltzmann-like transport; comparison with ray-by-ray approximation)

  (full 3D, energy-dependent transport @ 3D Cartesian grid)

  (2D, energy-dependent isotropic diffusion source approximation)
  (15, 20 $M_\odot$)

  (2D, energy-dependent multi-group flux-limited diffusion approximation)
  (12, 13, 15, 20, 25 $M_\odot$)

  (2D, energy-dependent isotropic diffusion source approximation)
  (11.2, 13, 15 $M_\odot$)

Not “complete” story yet - supernova problem not fully solved!
Magnetically-driven supernova explosions


Energetic bi-polar explosions

May explain existence of magnetars

Caveat: requires very high core spin and/or initial magnetic field of stellar core

Perhaps few rare events

Associated with production of $r$-process elements:


Beyond supernova explosion onset – once the stellar mantle is ejected . . .

The supernova story continues for more than 10 seconds!

Mildly independent from details of the supernova explosion mechanism

Can be modeled in spherical symmetry

\[ \nu_e + n \rightarrow p + e^- \]
\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

\(~ 20 - 30 \text{ km}~\)
\(~ T = 5 - 30 \text{ MeV} ~\)
\(~ E_\nu \sim 10^{53} \text{ erg} ~\)

low-mass outflow:

"\textbf{v-driven wind}"

(mass ejection from PNS surface)

\( \rho [\text{g} \cdot \text{cm}^{-3}] \)

10\(^{-14} \)

10\(^{6} \)

10\(^{10} \)

10\(^{4} \) km)

\( T \sim 0.25 \text{ MeV} \)

\( T \sim 0.5 \text{ MeV} \)

\( T \sim 1 \text{ MeV} \)

**PNS deleptonization**

*neutrino heating at PNS surface*

$\nu_e + n \rightarrow p + e^-$

$\bar{\nu}_e + p \rightarrow n + e^+$

$\nu \cdot \text{cm}^{-3}$

$T \sim 0.25 \text{ MeV}$

$T \sim 0.5 \text{ MeV}$

$T \sim 1 \text{ MeV}$

formation of heavy nuclei?

formation of seed nuclei

low-mass outflow:

"v-driven wind"

(mass ejection from PNS surface)

neutrino heating at PNS surface

PNS deleptonization

(neutrino diffusion)

$p$-process

(proton rich ($Y_e > 0.5$))

(neutron rich ($Y_e < 0.5$))

$\nu \cdot \text{cm}^{-3}$

$< 10$

$(> 10^4 \text{ km})$

$10^6$

$10^{10}$

$10^{14}$

$\rho \ [g \cdot cm^{-3}]$

$(\sim 100 \text{ km})$

$(\sim 20 - 30 \text{ km})$

$(E_\nu \sim 10^{53} \text{ erg})$
Nucleosynthesis is determined at $v$–decoupling

Deleptonization timescale:
\[ t = 10 - 30 \text{ s} \]

PNS deleptonization

formation of heavy nuclei?

formation of seed nuclei

low-mass outflow: "$v$-driven wind"
(mass ejection from PNS surface)

neutrino heating at PNS surface

PNS deleptonization
(neutrino diffusion)

proton rich ($Y_e > 0.5$)  
$vp$ process

neutron rich ($Y_e < 0.5$)  
neutron-capture process

$\nu_e + n \rightarrow p + e^-$

$\bar{\nu}_e + p \rightarrow n + e^+$

$T \sim 0.25 \text{ MeV}$

$T \sim 0.5 \text{ MeV}$

$T \sim 1 \text{ MeV}$

$\rho \text{ [g \cdot cm}^{-3}\text{]}$

$10^{14}$

$10^{10}$

$10^6$

$10^3$

$< 10$

$> 10^4 \text{ km}$

$\sim 100 \text{ km}$

$\sim 20 - 30 \text{ km}$

Numben of seed nuclei

formation of heavy nuclei?
Neutrino signal

Current models predict small spectral difference;

\[
Y_e \simeq \left( 1 + \frac{\varepsilon_{\bar{\nu}_e} - 2Q + 1.2Q^2/\varepsilon_{\bar{\nu}_e}}{\varepsilon_{\nu_e} - 2Q + 1.2Q^2/\varepsilon_{\nu_e}} \right)^{-1}
\]

(similar neutrino luminosities)

\[
\langle \varepsilon_{\bar{\nu}_e} \rangle - \langle \varepsilon_{\nu_e} \rangle \begin{cases} 
\gtrsim 5 \text{ MeV} & (Y_e < 0.5) \\
< 5 \text{ MeV} & (Y_e > 0.5)
\end{cases}
\]

(proton rich)

\[
\langle \varepsilon_{\nu} \rangle = \frac{\langle E_{\nu}^2 \rangle}{\langle E_{\nu} \rangle}
\]

Light neutron-capture elements $38 < Z < 45$: 

Martinez-Pinedo & TF et al., (2014) JPG 41, 044008

Hüdepohl et al., (2010) PRL 104, 251101

Roberts et al., (2012) PRC 86, 065803


TF et al., (2016) PRD (submitted)
Equation of state dependence of the neutrino signal
Excluded volume approach

Geometric approach; modifying the available volume:

\[ V_i = V \phi_i \]
\[ \phi_i = 1 - \sum_{j} v_j n_j \]

Excluded volume parameter:

\[ v \equiv v_n = v_p \]
\[ \phi(\rho; v) = \exp \left\{ -\frac{v|v|}{2}(\rho - \rho_0)^2 \right\} \]

(Gauss-functional)

DD2 – RMF parameters:
\[ K = 243 \text{ MeV} \]
\[ S = 31.67 \text{ MeV} \]
\[ L = 55.04 \text{ MeV} \]
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Geometric approach; modifying the available volume:

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Affects only supra-saturation density EOS; all other nuclear matter properties remain unchanged

Supernova neutrino signal is insensitive to supra-saturation density EOS
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Affects only supra-saturation density EoS; all other nuclear matter properties remain unchanged

Supernova neutrino signal is insensitive to supra-saturation density EOS
Quark-hadron phase transition

Extended transition region of instability

Pure quark-matter phase

Onset of quark-hadron mixed phase

Quark matter EoS: bag model with fixed bag pressure

Transition from some nuclear model (TM1)

Hadron-quark transition region: extended phase of instability; large latent heat

Sagert & TF et al., (2009) PRL 102, 081101
Quark-hadron phase transition

deleptonization burst form core bounce

Signal from strong 1st order phase transition at high densities

Sagert & TF et al. (2009), PRL 102, 081101

Dasgupta & TF et al. (2010), PRC 81

Luminosity $[10^{52}$ erg s$^{-1}]$
Quark-hadron phase transition

deleptonization burst from core bounce

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Summary
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Neutrino signal from core-collapse supernovae mildly insensitive to supra-saturation density EoS

Great progress in modeling, in particular in view of multi-dimensional nature
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Neutrino signal from core-collapse supernovae mildly insensitive to supra-saturation density EoS

Great progress in modeling, in particular in view of multi-dimensional nature

Massive star explosions (canonical) cannot explain galactic enrichment of heavy neutron-capture elements; 38<Z<45

Puzzle at low metallicity (?) – chemical evolution models:

(a) Core-collapse supernovae (SNe)  (b) Neutron star merger (NSM)

rate $\sim 10^{-2}$ yr$^{-1}$  rate $\sim 10^{-5}$ yr$^{-1}$

Consistent with metal-poor star observations (HD 122563)

Summary

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Puzzle at low metallicity (?) – chemical evolution models:

Role of light nuclear clusters (?) Requires consideration of associated weak processes consistent with EoS

TF. et al.,(2016) EPJWC.10906002F  
Nakamura et al.,(2001) PRC63, 034617  
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Any chance for quark matter (???) Develop more sophisticated (microscopic) quark matter EoS; chiral physics, finite temperatures and isospin asymmetry

\[ M_{\text{max}} \approx 2 \, M_\odot \]
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In collaboration with:

D. Blaschke  G. Martínez-Pinedo
M. Hempel  G. Röpke
T. Klähn  F.-K. Thielemann
M. Liebendörfer  Y. Suwa
K. Langanke  S. Typel
A. Lohs  M. R. Wu
Neutrino detection

MiniBooNE (200)  LVD (400)  Baksan (100)  Super-Kamiokande (10^4)  KamLAND (400)

Neutrino cross section in a water target detector

IceCube (10^6)

In brackets events for a “fiducial SN” at distance 10 kpc

(G.G. Raffelt)
The end of a massive star ($\gtrsim 9 \, M_\odot$)

Implosion of the stellar core due to pressure loss; triggered from $e^-$ captures on protons bound in nuclei

$$
e^- + ^{56}\text{Mn} \rightarrow ^{56}\text{Fe} + \nu_e$$
$$
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\[ \ldots \]
$$
e^- + \langle A, Z \rangle \rightarrow \langle A, Z - 1 \rangle + \nu_e$$

Collapsing stellar core neutronizes; electron fraction drops

$$(Y_e = n_p/n_B)$$

$Y_e > 0.5$ : neutron rich

$Y_e > 0.5$ : proton rich

$M_{\text{Core}} > M_{\text{CH}}$
Stellar core collapse

nuclear electron captures
\[ e^- + \langle A, Z \rangle \longrightarrow \langle A, Z - 1 \rangle + \nu_e \]

nuclear de-excitations
\[ \langle A, Z \rangle^* \longrightarrow \langle A, Z \rangle + \nu + \bar{\nu} \]

TF et al., (2013) PRC 88, 065804
(suppressed)
Stellar core collapse

Stellar collapse

Entropy per baryon \([k_B]\)

\[
\begin{align*}
\phantom{=} & \quad \text{core collapse} \quad \longrightarrow \quad \text{bounce} \\
2 & \quad \text{He} \\
10^5 & \quad ^{12}\text{C} \\
10^4 & \quad ^{16}\text{O} \\
10^3 & \quad ^{28}\text{Si}, ^{32}\text{S} \\
10^5 & \quad \text{Fe - core} \\
10^3 & \quad \text{elastic scattering on nuclei} \\
10^1 & \quad \text{neutrino free-streaming regime} \\
\end{align*}
\]

\[e^- + \langle A, Z \rangle \longrightarrow \langle A, Z - 1 \rangle + \nu_e\]

nuclear electron captures

\[\langle A, Z \rangle^* \longrightarrow \langle A, Z \rangle + \nu + \bar{\nu}\]

nuclear de-excitations

TF et al., (2013) PRC 88, 065804
(suppressed)

\[\nu_e + \langle A, Z \rangle \longrightarrow \langle A, Z \rangle + \nu_e\]

determines neutrino trapping

\[\langle E_\nu \rangle \text{[MeV]}\]

\[L_\nu \text{[10}^{52} \text{erg s}^{-1}]\]
Core bounce and shock formation

- Nuclear electron captures
  \[ e^- + \langle A, Z \rangle \rightarrow \langle A, Z - 1 \rangle + \nu_e \]
- Nuclear de-exitations
  \[ \langle A, Z \rangle^* \rightarrow \langle A, Z \rangle + \nu + \bar{\nu} \]

TF et al., (2013) PRC 88, 065804

Super nova shock
propagation across the
sphere of last inelastic
scattering (v-sphere)
\( v_e \)-deleptonization burst
(is generic feature)

Charged current reactions
\[ e^- + p \leftrightarrow n + \nu_e \]
\[ e^+ + n \leftrightarrow p + \bar{\nu}_e \]
Post bounce mass accretion

charged current reactions
\[ e^- + p \rightleftharpoons n + \nu_e \]
\[ e^+ + n \rightleftharpoons p + \bar{\nu}_e \]

pair processes
\[ e^- + e^+ \rightleftharpoons \nu + \bar{\nu} \]

elastic scattering
\[ \nu + N \rightleftharpoons \nu' + N \]

inelastic scattering
\[ \nu + e^\pm \rightleftharpoons \nu' + e^\pm \]
vBag approach to quark matter

\[ \mu_B \text{[MeV]} = \mu_{\chi} \]

\[ B_{\text{eff}}^{1/4} = 181.6 \text{ MeV} \]

\[ B_{\text{eff}}^{1/4} = 150.0 \text{ MeV} \]
Neutrino signal in multi-dim’l simulations

$L_{\nu} \left[10^{52} \text{ erg s}^{-1}\right]$

$(\nu_e, \bar{\nu}_e, \nu_\mu/\tau)$

Presence of millisecond variations of the neutrino signal

Induced from convection and associated shock oscillations

Persist even in detection on Earth

May allow distinction of strong bi-polar explosions
Production of heavy-element

Evolution of massive stars

Core-collapse supernovae (SN Ib,c II) vs. Neutron star mergers

Anders & Grevesse (1989) (too late, not frequent enough)

Argast et al. (2004) AA416,997

- slow (s) process (n-capture << decay)
  ➡ Stellar evolution

- rapid (r) process (n-capture >> decay)
  ➡ Explosive environment

- neutrino-induced (intermediate mass elements?)
Some relevant current equation of state constraints

- \( S \) . . . nuclear symmetry energy
- \( L \) . . . slope of the symmetry energy

Each EoS has a unique Mass-Radius relation

  (low-mass X-ray binary source analysis)