Supernovae as Nuclear and Particle Physics Laboratories

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- Introduction: Core-collapse supernova explosions
- The role of cold, ordered nuclear matter for the collapse phase and the emission of gravitational waves
- The role of hot high-density matter for the postbounce phase and the emission of neutrinos
- How would an early QCD phase transition impact SNe?
Supernova Observables

Gravitational waves
Neutron star kick and spin distributions
Gamma ray burst neutrino signal from interior

direct ejecta:
- composition
- velocity (spectra)
- asymmetry (polarization)

indirect ejecta
- mixing with ISM
- new star formation
- contamination of metal-poor stars
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Stellar evolution
Supernova theory
Nuclear Physics
Hydrodynamics
Radiative transfer
Supernova Observables

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Galactic evolution
Stellar evolution
Supernova theory
Nuclear Physics
Hydrodynamics
Radiative transfer
Make extreme conditions of matter observable...
Iron core collapse

Overview of burning phases in stellar evolution

- Fusion in core reaches maximum binding energy per baryon
- There is a maximum stable mass: Chandrasekhar mass

(Heger & Woosley 2002, see also Hirschi, Meynet, Maeder 2005)
Delayed explosion: 4 phases

Ensemble of nuclei
Freeze-out of nuclei
Hot dissociated matter
Cool bulk nuclear matter
 Freeze-out of nuclei
Microscopic input physics

Weak interactions between neutrinos and matter (Bruenn, ApJS 58, 1985 and Refs. therein)

- Coherent scattering of neutrinos on nuclei
  \[ \nu + (A, Z) \leftrightarrow \nu + (A, Z) \]
- Ion-ion correlations (Itoh 1975)
- Neutrino-electron scattering
  \[ \nu + e \leftrightarrow \nu + e \]
- Electron/neutrino capture on nuclei
  \[ \nu_e + (A, Z) \leftrightarrow e^- + (A, Z + 1) \]
- Electron/neutrino capture on nucleons
  \[ \nu_e + n \leftrightarrow e^- + p \]
  \[ \bar{\nu}_e + p \leftrightarrow e^+ + n \]
- Neutrino-nucleon scattering
  \[ \nu + N \leftrightarrow \nu + N \]
- Pair creation/annihilation
  \[ e^- + e^+ \leftrightarrow \nu + \bar{\nu} \]
- Nucleon-Nucleon bremsstrahlung (Thompson et al. 2002)
- Electron-\(\mu\) pair annihilation --\(\rightarrow\) muon-\(\mu\) pair creation (Buras et al. 2003)

Equation of state:
- charge neutrality
- nuclear statistical equilibrium (NSE)
- finite temperature
- Liquid drop
  (Lattimer-Swesty 1991)
- Brueckner HF
  (Shen et al. 1998)

Cool collapse

Hot postbounce
Observation <-> Model <-> Physics

**Spherical symmetry:**
- Excellent $n$-transport with detailed input physics
- 5 different codes give consistent results!

**Axisymmetry:**
- ray-by-ray or MGFLD $n$-transport
- computationally very expensive

**Three-dimensional:**
- $n$-transport approximations, separate domains
- enable 3D flow pattern & magnetic fields
  (Fryer & Warren 2002/4, Scheck et al. 2003, Ott et al. 2007, Scheidegger et al. 2008)

- Magneto-rotational explosion mechanism
  (Bisnovatyi-Kogan 1976, Leblanc & Wilson 1979,...)
- Delayed $n$-driven explosion mechanism & SASI
  (Colgate 1966, ... Marek & Janka, 2007)
- Acoustic explosion mechanism
  (Burrows et al. 2006)

No explosions obtained for most progenitors

Some explosions obtained, results not yet converged

Phenomenological studies
Cold matter in the collapse phase

- coherent neutrino-ion scattering (diffusion)

_density [g/cm^3]_

_energy [MeV]_

_radius [m]_

_center of star_

(Martinez-Pinedo, Liebendörfer, Frekers 2006)
Cold matter in the collapse phase

(Martinez-Pinedo, Liebendörfer, Frekers 2006)

- coherent neutrino-ion scattering (diffusion)
- electron capture

Density [g/cm³]
Energy [MeV]
Radius
Density [g/cm³]

center of star
Cold matter in the collapse phase

(Density [g/cm$^3$]

Energy [MeV]

- coherent neutrino-ion scattering (diffusion)
- electron capture
- neutrino-electron scattering (therm.)

Center of star

Martinez-Pinedo, Liebendörfer, Frekers 2006
Cold matter in the collapse phase

- coherent neutrino-ion scattering (diffusion)
- electron capture
- neutrino-electron scattering (therm.)

Density [g/cm$^3$]

Energy [MeV]

Radius

Center of star

region of main deleptonisation

strong blocking

low e-capture rates

Martinez-Pinedo, Liebendörfer, Frekers (2006)
Cold matter in the collapse phase

- coherent neutrino-ion scattering (diffusion)
- electron capture
- neutrino-electron scattering (therm.)

• the treatment of nuclear structure in n-rich nuclei causes 20% differences in location of shock formation!
Emission of Gravitational Waves

Galactic supernovae
-- could (LIGO)
-- should (Adv. LIGO)
be detectable (Scheidegger et al. 2008)

Fast rotating 15Ms progenitor
\( \nu \sim 2 \times 10^{-2} \text{ rad/ps} \)
--> imprint of bounce and rotation rate

Slowly rotating 15Ms progenitor according to
(Heger, Woosley & Spruit 2005)

Only type I GW signals are obtained!
(Dimmelmeier/Ott et al. 2007)

Galactic supernovae
-- could (LIGO)
-- should (Adv. LIGO)
be detectable
Testing cold matter at bounce?

- the direct impact is small!
- Is there an indirect impact on fluid instabilities that produce larger variations in GW emission?

Run1 --> K=180 MeV
Run2 --> K=375 MeV

Maximum density:
Run1 --> \( \rho = 3.8 \times 10^{14} \text{ g/cm}^3 \)
Run2 --> \( \rho = 3.6 \times 10^{14} \text{ g/cm}^3 \)

Maximum Amplitude (A+II at bounce):
Run1 --> A=506 cm
Run2 --> A=406 cm

Characteristic frequency:
Run1 --> \( f_c = 657 \text{ Hz} \)
Run2 --> \( f_c = 565 \text{ Hz} \)
Hot matter: Electron-neutrino signal

• initially similar luminosities
• differences appear in accretion phase
• >50% accretion lumin.
• density profiles in outer progenitor layers very different
• neutrino mean energy reflects neutrinospheric temperature
Sensitivity with respect to EoS

• Collapse, bounce, and postbounce evolution until black hole formation

• The quasi-static compression of the protoneutron star is reflected in mu/tau neutrino luminosities

• The different stiffness of the EoS causes very different delay times until BH formation

(Fischer et al. 2008, similar Sumiyoshi et al. 2007)
Signals of QCD phase transition?

- early discussion, revived by SN1987A neutrinos
  (e.g. Migdal et al. 1979, Takhara & Sato 1985-88)

- investigations with parameterised equations of state and GR hydrodynamics

- more realistic EoS’s and GR hydrodynamics (Gentile et al. 1993)

(Takahara & Sato 1986)

(Takahara & Sato 1988)

• select phase transition at or immediately after core bounce

• a second shock forms

• catches up with first shock

--> Is this observable?

• weak interactions and neutrinos neglected

• simulations only to few ms postbounce
Simple model for phase transition

- state-of-the-art GR Boltzmann neutrino transport
- Shen et al. 1998 equation of state for hadronic phase
- MIT bag model for quark phase, choosing parameters for early phase transition: $B^{1/4} = 162-165$ MeV, $m_s = 100$ MeV
- Mixed phase according to Gibbs construction (mechanical and chemical equilibrium, $n$'s trapped)


- 'just' compatible with heavy ion data
  - isospin-asymmetric
  - weak equilibrium allows for strange quarks

- 'just' compatible with neutron star data:
  - 162 supports 1.56 Ms
  - 165 supports 1.50 Ms
Neutrino signature of phase transition

Shown is a simulation of a 10 Ms star containing quark matter ($B^{1/4} = 162$) compared to one with hadronic matter only (black lines)

- strong second neutrino burst in all flavours
- electron anti-neutrinos dominate
- step up in neutrino rms energies

(I. Sagert et al., T. Fischer et al. 2008)
Origin of second neutrino burst

(Martinez-Pinedo, Liebendörfer, Frekers 2006)

- Quark/mixed phase only at high density
- \(\frac{m}{n}\)-spheres are at lower density

--> \(\frac{m}{n}\)'s not connected to quark physics

---> second luminosity peak must be an indirect effect!
Different dynamical stages

- collapse
- conversion to quark phase from inside out
- shrinking mixed phase
- second accretion shock propagating outward
- shock propagates with mixed-hadronic phase boundary

(Sagert et al., Fischer et al. 2008)
Different dynamical stages

- Shock propagates with mixed-hadronic phase boundary
- Accr. shock detaches from phase boundary to reach $n$-spheres in the hadronic phase

• Deleptonised matter becomes non-degenerate
• Weak equilibrium steps to larger $Ye$
• Pressure increases

(Sagert et al., Fischer et al. 2008)
Different dynamical stages

- accretion shock detaches from phase boundary to reach n-spheres in the hadronic phase
- shocked matter accelerates and triggers explosion

- deleptonised matter becomes non-degenerate
- weak equilibrium steps to larger Ye
- pressure increases

(Sagert et al., Fischer et al. 2008)
Different dynamical stages

- accr. shock detaches from phase boundary to reach \(n\)-spheres in the hadronic phase
- shocked matter accelerates and triggers explosion

- deleptonised matter becomes non-degenerate
- weak equilibrium steps to larger \(Ye\)
- pressure increases
- emission of anti-neutrino dominates when neutrino spheres are reached

(Sagert et al., Fischer et al. 2008)
Parameters, Progenitors & Nucleosynthesis

Larger bag constant
--> longer postbounce accretion time
--> more massive protoneutron star
--> deeper gravitational potential
--> larger peak luminosity in second neutrino burst
--> larger explosion energies

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<th>(M_Q)</th>
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\textsuperscript{a}moment of black hole formation
\textsuperscript{b}black hole formation before positive explosion energy is achieved

• Is tuning of parameters or the model of the quark phase possible to reproduce SN1987A?

• How do more massive progenitors explode?

• Weak \(n\)-driven explosion followed by phase transition?

• Some models eject low-Ye matter --> a possible site for the r-process?

(I. Sagert et al., T. Fischer et al. 2008)
Conclusions

• Deleptonisation of cold matter during collapse
  --> sensitive to e-capture
  --> and coherent scattering
  --> type I GW from 3D models

• Neutrino signal reflects PNS compressibility and accretion rate, sensitive to
  --> equation of state
  --> PNS thermal profile
  --> weak interaction rates

• Select bag constant for early QCD phase transition to quark matter
  --> second accretion shock
  --> anti-neutrino burst
  --> shift in rms energies
  --> triggers explosion